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Development and Investigation of Mechanical Properties on Eggshell Powder and Bamboo Fibre Reinforced Polycarbonate Bio-Composite Used for Prosthetic Implants

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Abstract: ***Polycarbonate (PC) is a high-performance thermoplastic valued for its impact resistance, toughness and dimensional stability. Bamboo fibre (BF) and eggshell powder (ESP), a calcium-carbonate-rich waste-derived filler, are potential reinforcements for developing hybrid polymer composites with renewable and waste-utilization benefits. This review examines the scientific basis for combining PC, BF and ESP, with emphasis on constituent characteristics, processing, fibre and particle interfaces, structure–property relationships, tribological behaviour and potential prosthetic or assistive applications. Published reviews of bamboo-fibre polymer composites and eggshell-derived calcium carbonate fillers are considered alongside recent direct evidence on bamboo-reinforced bio-polycarbonate. The literature indicates that reinforcement performance depends on fibre geometry, surface treatment, particle size, dispersion, moisture control and thermal history. Bamboo fibres can provide fibrous load transfer, while eggshell-derived particles may modify stiffness and hardness; however, weak interfaces, agglomeration and voids can reduce tensile strength and impact resistance. A critical processing issue is the need to melt-process PC without thermally damaging lignocellulosic fibres. The review identifies research needs in drying, compatibilization, processing-window optimization, impact and fatigue testing, wear characterization and environmental ageing. The available evidence supports further investigation of these materials for external prosthetic and assistive components, but it does not establish implant safety, biocompatibility or clinical suitability. The review provides a literature-based framework for subsequent experimental investigation of the ternary PC/BF/ESP system.***

Keywords: Polycarbonate, bamboo fibre, eggshell powder, calcium carbonate, hybrid polymer composite, interface engineering, prosthetic components.

I. INTRODUCTION

The development of lightweight, durable and economical engineering materials has encouraged the use of natural fibres and recovered mineral-rich wastes as reinforcements in polymer composites. Bamboo is an attractive lignocellulosic reinforcement because it is renewable, has relatively low density and can provide useful specific mechanical properties. Eggshell waste is a potential source of calcium carbonate ($CaCO_3$), a mineral filler widely used in polymer technology. Reviews of bamboo-reinforced polymers and bio-calcium-carbonate-filled composites describe the growing interest in these material systems, while emphasizing that their performance depends on matrix chemistry, processing and interface quality [1]–[4].

Polycarbonate is an engineering thermoplastic known for its impact resistance, toughness, transparency and dimensional stability. In a composite, PC forms the continuous matrix that binds reinforcement, transfers stress and maintains component geometry. Its melt processing requires careful control of moisture and thermal history because hydrolytic or thermal degradation can reduce molecular weight and impair mechanical performance [5].

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The combination of PC, bamboo fibre (BF) and eggshell powder (ESP) is of interest because the three constituents may provide complementary functions. Bamboo offers fibrous reinforcement, eggshell powder supplies a mineral particulate phase derived from waste, and PC provides a thermoplastic matrix. However, the final material is a multiphase system in which fibre polarity, particle dispersion, moisture, interfacial adhesion and processing temperature jointly influence performance.

This review critically discusses the material characteristics of PC, BF and ESP; processing and interface engineering; mechanical and tribological behaviour; and potential use in external prosthetic and assistive components. The experimental results in the associated project report are not presented as published literature data. Instead, the review focuses on published studies and identifies the research gap for subsequent experimental work.

II. REVIEW SCOPE AND APPROACH

The review is organized around five themes: (i) polycarbonate matrix characteristics and processing; (ii) bamboo fibre structure, treatment and polymer interfaces; (iii) eggshell-derived calcium carbonate as a particulate filler; (iv) structure–property relationships in hybrid composites; and (v) application prospects and validation requirements for prosthetic and assistive components. The discussion is narrative and critical rather than a statistical meta-analysis. Results from different studies are not pooled because matrix type, fibre architecture, filler size, loading, specimen preparation and test standards differ substantially.

Evidence from other polymer matrices is treated as adjacent evidence, not as direct proof of the behaviour of PC/BF/ESP. Particular attention is given to the recent study of bamboo-fibre-reinforced bio-polycarbonate, which provides direct but formulation-specific information on fibre surface treatment and processing [3].

III. CONSTITUENT MATERIALS

A. Polycarbonate as the Matrix Phase

PC is an amorphous engineering thermoplastic whose aromatic structure and carbonate linkages contribute to stiffness, toughness and impact resistance. Its relatively high glass-transition temperature and dimensional stability support use in engineering components. In a composite, the matrix binds the reinforcement, distributes applied stress, transfers load to fibres and particles, and provides a barrier against handling damage and environmental exposure.

The matrix is sensitive to processing history. Moisture in PC can promote hydrolytic chain scission at melt-processing temperatures, reducing molecular weight and potentially causing brittle mouldings. Processing guidance for PC emphasizes effective pre-drying and moisture control before moulding or extrusion [5]. This requirement is particularly important when bamboo fibre and eggshell powder are introduced, because both may carry adsorbed moisture unless appropriately conditioned.

B. Bamboo Fibre as a Renewable Reinforcement

Bamboo is a lignocellulosic material containing cellulose, hemicellulose and lignin. Its mechanical response is influenced by species, maturity, growing conditions, extraction method and fibre morphology. Cellulose-rich microfibrils provide the principal load-bearing structure, while hemicellulose and lignin contribute to the surrounding cell-wall architecture. Bamboo fibres may be used as continuous, aligned, woven, chopped or particulate reinforcement depending on the manufacturing route.

Reviews of bamboo-fibre-reinforced polymer composites report that fibre content, aspect ratio, orientation, extraction and treatment influence tensile and flexural properties [1], [2]. Moisture uptake and fibre–matrix incompatibility remain persistent challenges. The hydroxyl-rich surface of untreated lignocellulosic fibres is polar, whereas many engineering polymer matrices are comparatively less polar. Poor wetting can result in interfacial gaps, fibre pull-out and premature failure.

A recent study by Apostolidis et al. investigated untreated, alkali-treated and silane-treated bamboo fibres in bio-polycarbonate prepreg laminates consolidated by compression moulding. The authors reported improved interfacial adhesion and mechanical performance for the selected silane-treated fibres, while the tested alkali-treatment conditions did not consistently improve performance [3]. This finding demonstrates that treatment selection must be based on the chemistry of the particular fibre–matrix pair.

C. Eggshell Powder as a Bio-Derived Calcium-Carbonate Filler

Chicken eggshell is a mineralized biological waste stream whose inorganic fraction is predominantly calcium carbonate, commonly present in calcite form, together with smaller quantities of other inorganic constituents and residual organic membrane if it is not removed. Washing, drying, membrane management, grinding and sieving convert eggshell waste into a particulate filler. The powder may partly substitute conventional mined calcium carbonate in selected polymer formulations.

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Owuamanam and Cree reviewed eggshell- and seashell-derived bio-calcium-carbonate fillers in polymer composites and discussed their effects on tensile, flexural and impact properties, together with the role of surface modification [4]. Their review indicates that the response is matrix- and formulation-dependent: particulate calcium carbonate may increase stiffness or reduce material cost, but tensile strength and impact toughness may decline when particle dispersion and adhesion are inadequate. Homavand et al. reviewed eggshell/$CaCO_3$-filled PLA systems and likewise emphasized the dependence of composite properties on filler characteristics and formulation [6].

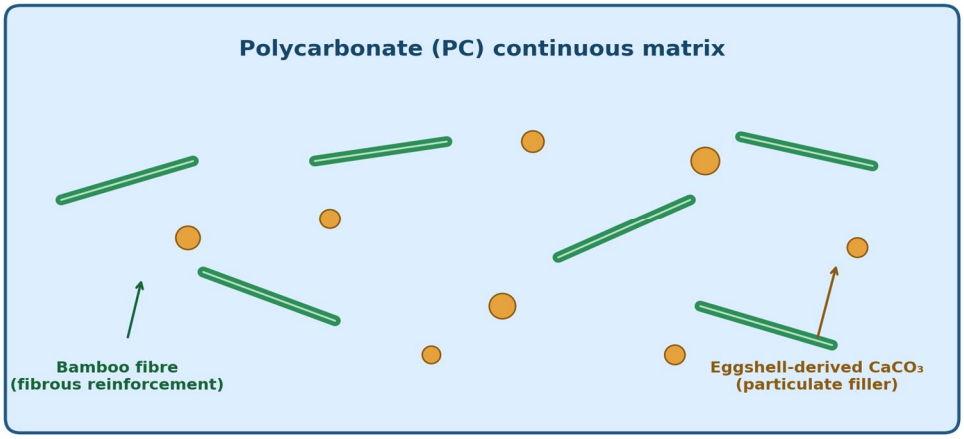


Fig. 1. Conceptual representation of the three phases in a PC/BF/ESP hybrid composite. Schematic prepared by the authors; it is not an experimental micrograph.

IV. PROCESSING OF PC/BF/ESP HYBRID COMPOSITES

A. Material Conditioning and Moisture Control

Moisture control is a first-order requirement. PC should be pre-dried according to the resin supplier's recommendations, while bamboo fibre and eggshell powder should be dried separately under conditions appropriate to their composition. Drying must remove moisture without thermally damaging the fibre or altering the filler. The dried constituents should be stored in sealed containers and transferred to compounding equipment with minimal exposure to ambient humidity. The exact drying schedule should be established experimentally using moisture measurement rather than assumed from a generic recipe.

B. Fibre Preparation and Surface Modification

Bamboo fibre preparation may include cleaning, size reduction, screening, controlled alkali treatment, silane treatment or other coupling strategies. Alkali treatment can remove surface impurities and alter fibre roughness, but excessive concentration or exposure can damage the fibre cell wall. Silane coupling agents may provide a chemical bridge between the hydroxyl-rich fibre surface and a polymer-compatible phase. Their effectiveness depends on hydrolysis, condensation, surface coverage and processing conditions. The direct bio-polycarbonate study provides evidence that silane treatment can improve the tested bamboo/bio-PC laminate system [3].

C. Eggshell Powder Preparation and Particle Control

Eggshell preparation should ensure consistent cleanliness, membrane treatment, drying and particle-size distribution. Grinding without subsequent sieving can produce a broad particle-size distribution, while very fine grinding may increase surface area and agglomeration tendency. Particle size should be reported together with the measurement method, and the powder should be characterized for morphology, composition and moisture. Surface modification or a suitable compatibilizer may improve wetting by the polymer matrix, but should be selected only after compatibility and thermal-stability assessment.

D. Melt Compounding and Consolidation

Twin-screw extrusion is a possible route for dispersing fibres and particulate fillers within a thermoplastic matrix because screw configuration and feeding position can be adjusted to control mixing and shear. High shear can shorten fibres, whereas insufficient mixing can leave agglomerates and voids. A staged feeding strategy may be useful: PC is first plasticized, followed by controlled

addition of dried filler and fibre, with screw speed, temperature profile and residence time optimized to balance dispersion and fibre preservation. Compression moulding or injection moulding can then be used to produce components or test specimens.

A major challenge is the mismatch between the processing temperature required to melt and flow PC and the thermal sensitivity of natural fibres. The process window should be determined from thermal analysis and melt rheology of the actual constituents rather than relying on a single nominal temperature. Processing history also influences matrix degradation, fibre attrition, particle dispersion, void fraction and residual stress.

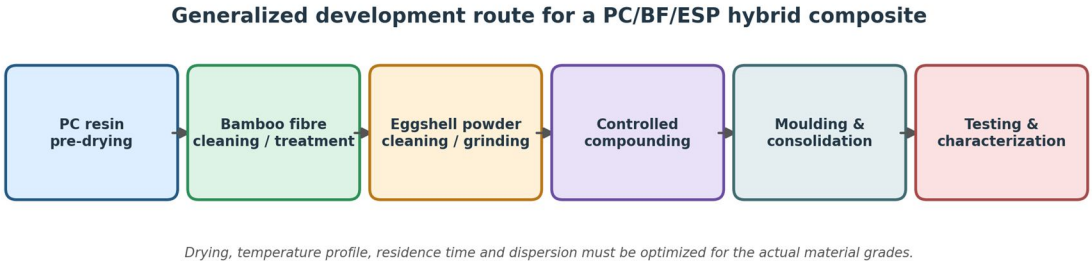


Fig. 2. Generalized processing sequence for developing PC/BF/ESP hybrid composites. Schematic prepared by the authors.

E. Process–Structure Relationships

The principal process variables are melt temperature, residence time, screw speed, fibre feeding sequence, fibre length after compounding, powder size, moisture content, compatibilizer concentration, mould temperature and cooling rate. These variables influence matrix degradation, fibre attrition, particle dispersion, void fraction and interfacial contact. Process optimization should therefore combine mechanical testing with microscopy, thermal analysis and rheological measurements.

V. INTERFACIAL COMPATIBILITY AND MICROSTRUCTURE

The hybrid composite contains at least three distinct phases: a continuous PC matrix, a fibrous bamboo phase and a particulate eggshell-derived mineral phase. The fibre–matrix interface controls stress transfer from PC to bamboo, while the particle–matrix interface controls the extent to which mineral filler contributes to stiffness and wear resistance. A weak interface can cause debonding, pull-out and void formation, whereas a brittle interface may promote crack initiation.

For bamboo fibres, the polarity difference between the fibre surface and polymer matrix is a key source of incompatibility. Surface modification, coupling agents and compatibilizers can improve wetting and load transfer, but the optimum treatment is matrix-specific. Reviews by Radzi et al. and Yu et al. describe the influence of fibre treatment, processing and moisture on bamboo/polymer composite properties [1], [2]. The recent bio-PC study adds direct evidence that silane treatment can improve the tested bamboo/bio-PC laminate system [3]. For eggshell powder, key variables include particle size, surface chemistry, residual membrane, moisture, particle shape and dispersion. At low or moderate loadings, well-dispersed rigid particles may increase modulus or hardness. At higher loadings, agglomeration and poor wetting can generate local stress concentrations and reduce tensile or impact performance [4], [6]. A useful microstructural assessment should combine scanning electron microscopy (SEM) with complementary methods. SEM can reveal fibre pull-out, matrix coating, voids, fracture paths and particle agglomerates. Energy-dispersive X-ray spectroscopy can confirm the presence of elements such as calcium, but it does not by itself establish uniform three-dimensional dispersion or identify all chemical phases. X-ray diffraction can support phase identification, while Fourier-transform infrared spectroscopy can indicate changes in chemical functional groups.

VI. STRUCTURE–PROPERTY RELATIONSHIPS

A. Tensile Behaviour

Tensile strength depends on the ability of the matrix to transfer stress to bamboo fibres and on the extent of defects within the composite. Well-aligned fibres with adequate interfacial adhesion can carry load and increase strength or stiffness. Randomly oriented short fibres may provide less efficient reinforcement, particularly when fibre length is reduced during compounding. Agglomerated eggshell particles and voids can act as crack-initiation sites. Consequently, the effect of adding BF and ESP cannot be expressed as a universal monotonic trend.

B. Flexural Behaviour

Flexural loading creates a stress gradient through the specimen thickness, with tensile stresses on one surface and compressive stresses on the opposite surface. Fibre orientation, matrix continuity, particle distribution and interfacial adhesion influence the flexural response. Bamboo fibres may improve flexural stiffness when appropriately oriented and bonded, while poorly bonded interfaces can lead to early cracking. Mineral filler can increase stiffness but may reduce flexural strength if agglomerates or voids dominate failure.

C. Compressive Behaviour

Compression performance is influenced by matrix yielding, fibre buckling or kinking, local shear and the stability of the fibre–matrix interface. Particulate $CaCO_3$ may restrict local matrix deformation, but excessive loading can create particle-rich regions that fracture or debond. For prosthetic components, compression testing alone is insufficient because service loading is repeated, multiaxial and includes impact and bending.

D. Impact and Fracture Toughness

PC is selected in many engineering applications partly because of its toughness and impact resistance. Reinforcement can improve stiffness but may reduce the energy-absorbing deformation of the matrix, especially when rigid particles or poorly bonded fibres introduce stress concentrations. The balance between strength, stiffness and toughness is therefore central to design. Charpy or Izod impact testing, fracture-surface examination and instrumented impact testing should be included in future formulation studies.

E. Tribological Behaviour and Wear

Wear behaviour is controlled by matrix hardness, filler hardness, interfacial stability, counterface roughness, contact pressure, sliding speed, temperature and debris formation. A well-dispersed mineral phase may reduce matrix deformation under sliding contact, but particle pull-out can create third-body abrasive debris and accelerate wear. Bamboo fibres may influence friction and wear through surface exposure, fibre fracture and transfer-film formation. A valid comparison requires a clearly specified wear configuration, counterface, load, speed, sliding distance, conditioning and mass- or volume-loss calculation. Abrasion, pin-on-disc and other tribological methods are not interchangeable; the selected standard and apparatus must match the reported test.

F. Water Absorption and Environmental Ageing

Bamboo is moisture-sensitive. Water uptake can cause fibre swelling, interfacial stress and dimensional change, while repeated wetting and drying may weaken the interface. UV exposure, temperature cycling and chemical contact can further alter polymer and fibre performance. A recent review of bamboo-fibre-reinforced polymer composites identifies moisture, hygrothermal exposure, UV radiation and other ageing conditions as important durability factors [7]. Long-term service claims should therefore be based on environmental ageing tests rather than initial mechanical properties alone.

VII. COMPARISON OF EVIDENCE FROM RELATED MATERIAL SYSTEMS

Table I summarizes the relevance and limitations of selected literature. Numerical values are not pooled because the studies use different matrices, fibre architectures, filler sizes and processing routes.

Study / material system	Main contribution	Relevance to PC/BF/ESP	Limitation
Radzi et al. [1]; bamboo fibre in polymer matrices	Reviews fabrication, properties and applications of bamboo-fibre composites.	Establishes roles of fibre treatment, loading, matrix choice and moisture.	Not specific to eggshell-filled PC.
Yu et al. [2]; bamboo-fibre polymer composites	Reviews processing, mechanical behaviour, moisture uptake and interface performance.	Provides a framework for fibre geometry and processing selection.	Broad review; outcomes vary across matrices.
Apostolidis et al. [3]; bamboo-fibre bio-polycarbonate	Compares untreated, alkali- and silane-treated fibres in bio-PC laminates.	Direct evidence that fibre surface chemistry matters in a PC-family matrix.	Bio-PC laminate route may differ from conventional PC/short-fibre/ESP

			compounds.
Owuamanam and Cree [4]; eggshell/seashell $CaCO_3$ in polymers	Reviews mechanical effects and surface modification of bio-calcium-carbonate fillers.	Supports eggshell-derived mineral filler and highlights interface trade-offs.	Multiple matrices; not direct validation in PC.
Homavand et al. [6]; eggshell/$CaCO_3$-filled PLA	Reviews eggshell/$CaCO_3$ effects on PLA composite properties.	Shows that mineral-filler response depends on matrix and loading.	PLA differs chemically and thermally from PC.
Shettigar et al. [7]; ageing of bamboo-fibre polymer composites	Reviews water, hygrothermal, UV and other ageing effects.	Identifies durability tests needed for natural-fibre hybrids.	Does not establish lifetime of the ternary PC/BF/ESP system.

Table I. Summary Of Selected Literature And Its Relevance To The Ternary Composite

VIII. POTENTIAL PROSTHETIC AND ASSISTIVE APPLICATIONS

The mechanical and processing characteristics of PC-based composites make them candidates for investigation in external prosthetic and assistive products. Examples include non-implant structural covers, cosmetic limb shells, protective housings, orthotic support elements, wheelchair accessories and rehabilitation-equipment enclosures. A prosthetic foot or other load-bearing component requires substantially more demanding validation because it experiences repeated bending, impact, fatigue and variable environmental exposure.

A numerical study of a polycarbonate structural core combined with microcellular rubber for a prosthetic foot illustrates interest in PC-based structural elements and hybrid cushioning concepts [8]. That study concerns a PC/rubber design and does not demonstrate the suitability of bamboo/eggshell-filled PC. It is therefore adjacent evidence for PC in prosthetic design, not clinical validation of the present ternary material.

The distinction between an external assistive component and an implant is essential. A material intended for prolonged direct contact with tissue or implantation must undergo appropriate biological evaluation, chemical characterization, sterilization assessment and regulatory review. Mechanical testing does not establish biocompatibility. The evidence reviewed here does not justify claims that PC/BF/ESP is non-toxic, implant-safe or clinically approved.

IX. KEY CHALLENGES AND RESEARCH GAPS

1) Processing-window compatibility: PC melt processing and bamboo thermal stability must be reconciled through controlled temperature profiles, short residence times, pre-drying and thermal analysis of the actual fibre grade.

2) Fibre–matrix interface: untreated, alkali-treated and silane-treated bamboo should be compared systematically, with treatment concentration and exposure conditions fully reported.

3) Particle dispersion: eggshell particle-size distribution, shape, surface chemistry and loading should be optimized to prevent agglomeration and void formation.

4) Ternary interaction effects: the combined effect of fibre and mineral filler may not equal the sum of their individual effects. Factorial or response-surface designs are needed to identify interactions.

5) Mechanical performance balance: tensile, flexural, compressive, impact and fatigue properties should be considered together rather than optimizing a single strength metric.

6) Tribological validation: wear tests should use a clearly stated standard and controlled contact conditions, with wear rate, friction coefficient and wear-surface morphology reported.

7) Thermal and rheological characterization: differential scanning calorimetry, thermogravimetric analysis, dynamic mechanical analysis and melt-rheology measurements are needed to assess processing stability and service-temperature limits.

8) Environmental durability: water absorption, wet–dry cycling, UV exposure, thermal cycling and chemical resistance should be investigated over relevant durations.

9) Biological and regulatory evaluation: any intended skin-contact or implant-related application requires risk-based biological evaluation, chemical characterization and relevant regulatory compliance.

10) Life-cycle and cost assessment: the environmental value of eggshell reuse and bamboo reinforcement should be quantified through sourcing, processing-energy, transport and end-of-life analyses.

X. RECOMMENDED RESEARCH FRAMEWORK

A staged research programme would reduce uncertainty and avoid attributing performance changes to the wrong constituent. First, characterize PC resin, bamboo fibre and eggshell powder independently. For bamboo, record species, source, extraction route, fibre length and diameter distribution, moisture content and surface chemistry. For eggshell powder, report cleaning and membrane-removal procedure, drying conditions, particle-size distribution, phase composition and morphology. For PC, report grade, melt-flow information and supplier-recommended drying and processing conditions.

Second, establish a processing window using thermogravimetric analysis of the fibre and filler, moisture measurements, and melt-rheology or melt-flow tests of the matrix. Third, prepare a controlled formulation matrix that includes neat PC, PC/BF, PC/ESP and PC/BF/ESP controls. This design makes it possible to distinguish the contribution of each reinforcement and their interaction. Fibre and filler fractions should be varied systematically while keeping the total composition and processing history traceable.

Fourth, characterize the resulting materials using tensile, flexural, compression, impact, hardness, wear, dynamic mechanical analysis, differential scanning calorimetry and thermogravimetric analysis, with appropriate standards and replicate counts. SEM should be used to examine fracture morphology, while energy-dispersive X-ray spectroscopy, X-ray diffraction and Fourier-transform infrared spectroscopy provide complementary chemical and phase information. Fifth, conduct water absorption, UV/humidity ageing, thermal cycling and fatigue tests before selecting any component-level application.

For prosthetic and assistive use, the design stage should translate material data into component-level requirements: load spectrum, safety factor, allowable deformation, fatigue life, wear, environmental exposure, user comfort, repairability and cost. A prototype should be evaluated under representative loading and, where appropriate, standardized prosthetic component testing. Biological evaluation is required if the finished device has relevant patient contact.

XI. CONCLUSION

Bamboo fibre and eggshell-derived calcium carbonate offer complementary reinforcement opportunities for polycarbonate-based hybrid composites. Bamboo can contribute fibrous load transfer and renewable content, while eggshell powder can provide a waste-derived mineral filler. PC provides a tough thermoplastic matrix, but the final properties depend on fibre treatment, particle dispersion, interfacial adhesion, moisture control and thermal processing history.

Published reviews establish the promise and limitations of bamboo-fibre polymer composites and eggshell/$CaCO_3$-filled polymers. A recent direct study on bamboo-fibre-reinforced bio-polycarbonate further demonstrates that surface modification can improve interfacial performance in the investigated material system. Nevertheless, results from other matrices and bio-PC laminates cannot be transferred uncritically to conventional PC containing both bamboo fibre and eggshell powder.

The most important unresolved issue is the processing and interface design of the complete ternary system. Future work should combine careful drying, controlled fibre treatment, particle-size optimization, compatibilization and systematic mechanical, thermal, rheological, tribological and ageing tests. The material may warrant investigation for external prosthetic and assistive components, but current evidence does not establish implant suitability or biocompatibility. Such claims require dedicated biological, chemical, durability and regulatory evaluation.

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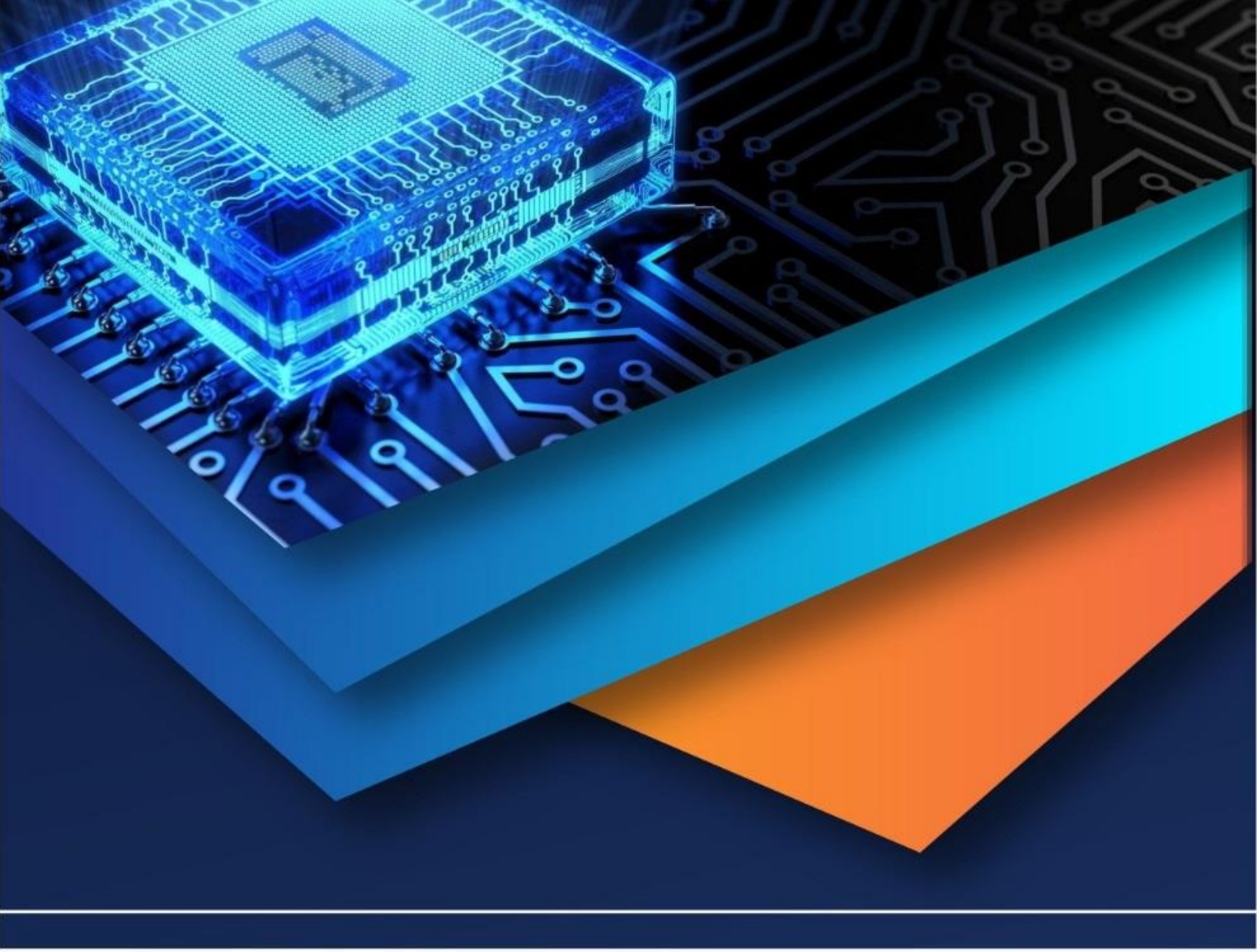
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