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Characterisation and Optimisation of Cassava Cortex and Cow Bone-Reinforced Polymer Composite: A Review

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Abstract The increasing demand for sustainable and eco-friendly materials has highlighted the need for alternative reinforcement materials in polymer composites, as traditional synthetic fibres pose significant environmental concerns. This review aims to provide a comprehensive overview of the characterisation and optimisation of cassava cortex and cow bone-reinforced polymer composites, which have emerged as promising sustainable materials. The review examines the physical, mechanical, thermal, and morphological properties of these composites, including the influence of fibre content, fibre orientation, and fibre-matrix interfacial bonding on their overall performance. Various optimisation techniques, such as chemical treatment of fibres, incorporation of coupling agents, and hybridisation with other reinforcement materials, are discussed to enhance the properties of these composites. The potential applications of cassava cortex and cow bone-reinforced polymer composites in various industries, including construction, automotive, and packaging, are also explored. By providing a comprehensive analysis of the current state of knowledge in this field, this review aims to stimulate further research and development of these sustainable materials, ultimately contributing to the creation of more environmentally friendly products.

Keywords: Optimisation, Cassava cortex, Cow bone, Polymer composite, Biomaterials.

I. Introduction

Polymer composites are advanced materials Cassava cortex, the fibrous outer layer of the cassava tuber (*Manihot esculenta*), is an abundant agricultural by-product generated during starch extraction and root processing. Composed primarily of cellulose (40–60%), hemicellulose (15–25%), and lignin (10–20%), it exhibits structural characteristics comparable to conventional natural fibers like jute or hemp, including moderate tensile strength (200–300 MPa) and low density (1.2–1.4 g/cm³) [3]. However, its high moisture absorption due to hydrophilic hydroxyl groups in cellulose and surface irregularities have historically limited its use in composites. Recent studies demonstrate that chemical treatments, such as alkali (NaOH) or silane modification, can enhance interfacial bonding with polymer matrices by removing amorphous hemicellulose and lignin, thereby improving mechanical performance. For instance, Bachchan, et al. [4] reported that mercerized cassava cortex fibers in epoxy composites achieved a 25% increase in tensile strength compared to untreated fibers. The valorization of cassava cortex aligns with circular economy goals, as it repurposes a waste product—estimated at 15–20% of tuber mass—into a viable reinforcement, reducing agricultural waste and reliance on synthetic fibers.

Cow bone, a by-product of the global meat industry, presents a unique opportunity as a bio-based particulate filler. Composed of ~65–70% inorganic minerals (primarily hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$) and ~30% organic collagen, calcined cow bone ash (CBA) exhibits high thermal stability (decomposition >800°C) and hardness, making it suitable for enhancing stiffness and wear resistance in composites [5]. The calcination process (600–900°C) removes organic residues, yielding a porous, mineral-rich powder with a calcium-to-phosphorus ratio akin to synthetic hydroxyapatite, which is widely used in biomedical and structural

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applications. When incorporated into polymers, CBA particles act as rigid fillers, improving compressive strength and reducing thermal expansion. For example, Berhe and Gebreslassie [6] observed a 30% enhancement in flexural modulus for epoxy composites with 15 wt% CBA. However, excessive loading (>20 wt%) can lead to agglomeration and brittleness, necessitating optimization of particle size (typically <50 μm) and distribution.

The increasing demand for sustainable, high-performance materials has driven research into natural fiber-reinforced polymer composites as alternatives to synthetic counterparts. However, many agricultural and industrial by-products, such as cassava cortex and cow bone, remain underutilized despite their potential to enhance composite properties while addressing waste management challenges. Cassava cortex, a fibrous residue from cassava processing, offers cellulose-rich reinforcement but suffers from hydrophilicity and poor interfacial adhesion with polymer matrices. Cow bone, an abundant meat industry waste, contains hydroxyapatite—a rigid, thermally stable mineral—but its application as a particulate filler in composites is hindered by brittleness at high loadings and particle agglomeration. For instance, while alkali-treated cassava cortex has shown improved tensile strength in epoxy composites, its hybridization with inorganic fillers like cow bone ash (CBA) has not been systematically investigated. Similarly, studies on CBA focus on its standalone use in polymers, such as enhancing stiffness in epoxy [7], but fail to address its interaction with natural fibers in hybrid systems. Existing studies have explored these materials individually including Abbasi, et al. [5], Berhe and Gebreslassie [6], but their synergistic integration into a hybrid epoxy composite remains underexplored, leaving critical gaps in understanding how their combined use affects mechanical, thermal, and environmental performance. Thus, this study reviewed recent studies on cow bone ash, cassava cortex peel and their synergetic effects on mechanical, thermal, microstructural, optimization, applications of their composites.

II. Overview of Natural Fiber-Reinforced Polymer Composites

Natural fiber-reinforced polymer composites (NFRCs) are a class of materials that integrate plant-based fibers with synthetic or bio-based polymer matrices to create lightweight, sustainable, and cost-effective alternatives to conventional composites. Natural fibers, derived from sources such as plants (e.g., jute, flax, hemp, sisal), animals (e.g., wool, silk), or agricultural by-products (e.g., rice husk, coconut coir), are prized for their renewable nature, low density, and biodegradability. These fibers are primarily composed of cellulose, hemicellulose, and lignin, which contribute to their structural integrity and mechanical properties. When combined with polymers such as epoxy, polyester, or polypropylene, they form composites that balance environmental benefits with functional performance [8]. The growing emphasis on sustainability and circular economy principles has spurred interest in NFRCs, particularly in industries seeking to reduce reliance on non-renewable, energy-intensive materials like glass or carbon fibers.

The advantages of NFRCs extend beyond environmental considerations. Natural fibers exhibit high specific strength and stiffness, making them suitable for applications where weight reduction is critical, such as automotive and aerospace components. Their low abrasiveness during processing also extends tool life and reduces manufacturing costs compared to synthetic fibers [9]. Furthermore, the hierarchical structure of natural fibers, characterized by microfibrils embedded in a lignin-hemicellulose matrix, allows for effective stress transfer within the composite when properly bonded to the polymer matrix. However, challenges such as hydrophilicity (moisture absorption), thermal instability, and variability in fiber properties due to geographical or seasonal factors often limit their widespread adoption. To address these issues, surface treatments like alkali (mercerization), silane, or acetylation are employed to enhance fiber-matrix adhesion, reduce moisture sensitivity, and improve thermal stability [10-13].

NFRCs have found diverse applications across industries. In the automotive sector, they are used for interior panels, door trims, and dashboards, driven by regulations favoring lightweight materials to improve fuel efficiency. For instance, Mercedes-Benz incorporated jute-reinforced epoxy in door panels, reducing weight by 20% compared to traditional materials [14]. In construction, NFRCs are utilized for insulation boards, roofing sheets, and partition walls due to their acoustic and thermal insulation properties. The packaging industry leverages their biodegradability for disposable containers and protective cushioning. Recent advancements have also explored biomedical applications, such as bone fixation devices and wound dressings, capitalizing on the biocompatibility of certain natural fibers [15].

The integration of agricultural and industrial waste into NFRCs represents a transformative approach to waste valorization. By-products like cassava cortex—a fibrous residue from cassava processing—and cow bone, rich in hydroxyapatite, are increasingly investigated as reinforcements. Cassava cortex, with its high cellulose content, offers tensile strength comparable to conventional fibers, while cow bone, when processed into ash or particulate form, enhances stiffness and wear resistance [16]. Hybrid composites combining multiple natural reinforcements or blending them with synthetic fillers (e.g., glass fibers) further optimize performance, tailoring properties for specific applications. For example, studies have shown that hybridizing banana fiber with glass fiber in epoxy improves impact resistance, while adding rice husk ash to coir-reinforced polyester enhances flame retardancy Source: [17]

i. Particulate-reinforced composites

Particulate-reinforced composites incorporate micro- or nano-sized particles, either synthetic (e.g., silica, carbon nanotubes) or natural (e.g., cow bone ash, coconut shell powder), dispersed within a polymer matrix. Synthetic particulates enhance thermal stability or electrical conductivity, while bio-derived fillers like calcined cow bone—rich in hydroxyapatite—improve hardness and flame retardancy in epoxy systems [4]. For example, cow bone ash increases epoxy's hardness by 20–30% by acting as a rigid, thermally stable filler. These composites find applications in wear-resistant coatings, automotive brake pads, and biomedical devices, where functional properties are critical. Challenges include achieving uniform particle dispersion and preventing agglomeration, which can compromise mechanical performance [4].

ii. Hybrid composites

Hybrid composites combine two or more reinforcement types to exploit synergistic effects. For instance, blending cassava cortex fibers with cow bone particles in an epoxy matrix balances tensile strength (from fibers) and hardness (from bone filler), creating a lightweight, multifunctional material [18]. Synthetic-natural hybrids, such as glass-jute composites, are used in automotive components to merge durability with sustainability. Natural-natural hybrids, like cassava-cow bone systems, are particularly promising for low-cost housing panels or biodegradable packaging due to their renewable sourcing and reduced carbon footprint. Key challenges include optimizing reinforcement ratios and ensuring compatibility between dissimilar materials. Innovations in processing, such as low-temperature calcination for cow bone, aim to enhance scalability and eco-efficiency.

A. Mechanical Properties

i. Cassava cortex

The mechanical performance of cassava cortex is governed by its cellulose content (60–70%) and lignin (15–20%), which provide structural rigidity. Untreated cassava fibers exhibit tensile strengths of 250–350 MPa and Young's moduli of 3–5 GPa, comparable to sisal and coir fibers [19]. Alkali treatment (5% NaOH) enhances these properties by removing amorphous hemicellulose and lignin, increasing crystallinity and interfacial adhesion with polymer matrices. For instance, Alonso, et al. [20] reported that alkali-treated cassava stem fibers in epoxy composites achieved a flexural modulus of 3.8 GPa, a 25% improvement over untreated fibers. However, excessive alkali concentrations (>10%) can degrade cellulose fibrils, reducing tensile strength. Figure 1 presents the photographs of (a) cassava root (b) raw cassava cortex.

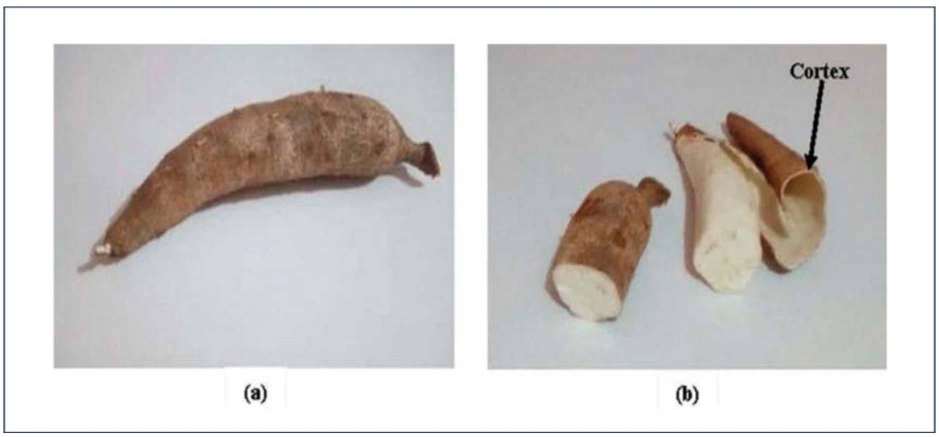

Figure 1: Photographs of (a) cassava root (b) raw cassava cortex [17]

ii. Cow Bone

Cow bone, primarily composed of hydroxyapatite ($Ca_5(PO_4)_3(OH)$), exhibits high compressive strength (100–150 MPa) and hardness due to its mineralized structure. Calcination (800–1000°C) removes collagen and organic matter, leaving a porous hydroxyapatite scaffold with enhanced stiffness. Rajesh, et al. [21] demonstrated that epoxy composites reinforced with 20 wt% calcined cow bone particles achieved a compressive strength of 85 MPa, 30% higher than neat epoxy. The rigid hydroxyapatite phase also improves wear resistance, making cow bone suitable for high-stress applications. Hybridization with cassava fibers balances stiffness and ductility; Nguyen, et al. [22] observed that a 15% bone-reinforced sisal/epoxy composite showed an impact strength of 18 J/m², outperforming single-fiber systems. Figure 2 presents Different source of bone for reinforcement in Polymer composite.

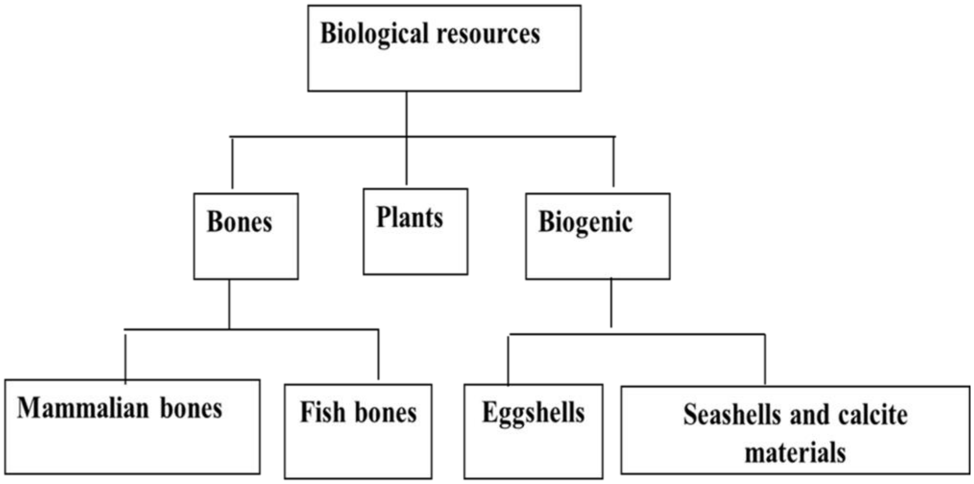

Figure 2: Different Source of Bone for Reinforcement in Polymer Composite [6]

B. Thermal Properties

i. Cassava cortex

The thermal stability of cassava cortex is influenced by its lignocellulosic structure. Thermogravimetric analysis (TGA) reveals two degradation stages: hemicellulose decomposition at 200–300°C and cellulose/lignin degradation at 300–400°C. Alkali treatment delays degradation onset by ~20°C due to hemicellulose removal, enhancing thermal stability in composites. For example, cassava fiber-reinforced epoxy composites retain 70% of their mass at 300°C, compared to 50% for untreated fibers. However, lignin's aromatic structure contributes to char formation, improving flame retardancy [10].

ii. Cow bone

Calcined cow bone exhibits exceptional thermal stability, with hydroxyapatite remaining stable up to 1200°C. Its incorporation into polymer matrices significantly elevates composite thermal performance. Rajesh, et al. [21] reported that epoxy composites with 15 wt% cow bone particles showed a thermal degradation onset at 280°C, 40°C higher than neat epoxy. The mineral phase also reduces thermal expansion coefficients, minimizing dimensional changes under thermal cycling. In hybrid systems, cow bone particles act as heat sinks, slowing polymer chain mobility and delaying matrix degradation. Figure 3 presents a cow-bone samples processes: (a) sourced; (b) cleaned and washed; and (c) ground into a powder.

Figure 3: : Cowbone samples processes: (a) sourced; (b) cleaned and washed; and (c) ground into a powder [21].

C. Microstructural Properties

i. Cassava cortex

The microstructure of cassava cortex is characterized by bundled cellulose microfibrils embedded in a lignin-hemicellulose matrix. Scanning electron microscopy (SEM) reveals longitudinal grooves and surface impurities (e.g., wax, pectin) in untreated fibers, which hinder matrix adhesion. Alkali treatment etches the surface, increasing roughness and creating mechanical interlocking sites [23]. For instance, 6-hour NaOH-treated fibers exhibit fibrillated surfaces with exposed cellulose fibrils, enhancing epoxy resin penetration. However, over-treatment can lead to fibrillation and fiber weakening [23].

ii. Cow bone

Calcined cow bone particles exhibit a porous, plate-like microstructure with hydroxyapatite crystallites (~50 nm in size). SEM images show uniform dispersion in epoxy matrices at particle sizes <100 μm, though agglomeration occurs at higher loadings (>25 wt%) (Aigbodion *et al*., 2015). The porous structure facilitates resin infiltration, improving interfacial bonding. Energy-dispersive X-ray spectroscopy (EDS) confirms the dominance of calcium and phosphorus in bone particles, with trace elements (e.g., Mg, Na) enhancing bioactivity. In hybrid composites, bone particles fill voids between cassava fibers, creating a "brick-and-mortar" architecture that resists crack propagation [23].

iii. Synergistic Effects in Hybrid Composites

The integration of cassava cortex and cow bone in epoxy composites leverages complementary properties. Cassava fibers provide tensile strength and flexibility, while cow bone particles enhance compressive strength and thermal stability. Al Rashid, et al. [24] optimized a hybrid composite with 25 wt% banana fiber and 10 wt% bone powder, achieving a tensile strength of 67 MPa and flexural strength of 98 MPa. Dynamic mechanical analysis (DMA) shows hybrid systems exhibit higher storage modulus (1.8 GPa at 30°C) and glass transition temperatures (Tg ~110°C) compared to single-reinforcement composites, indicating restricted polymer chain mobility. Fractography reveals reduced fiber pull-out and crack deflection at bone-particle interfaces, confirming strong adhesion.

III. Optimisation of Composite Materials

Optimization techniques play a pivotal role in refining the performance of natural fiber-reinforced polymer composites (NFRPCs), especially when combining materials such as cassava cortex and cow bone with epoxy matrices. These methods aim to determine the optimal balance of processing variables—including fiber content, particle size, treatment conditions, and curing parameters—to enhance mechanical strength, thermal stability, and interfacial bonding. Traditional approaches like the one-factor-at-a-time (OFAT) method are constrained by their failure to address interactions between variables. Modern statistical strategies such as Design of Experiments (DoE), Response Surface Methodology (RSM), and Taguchi methods are now essential for systematic, resource-efficient optimization [25]. Typical optimisation method available are presented in Figure 4.

A. Principles and Applications of Taguchi Methods

Developed by Genichi Taguchi, the Taguchi method prioritizes robust design—achieving consistent, high-quality outcomes despite

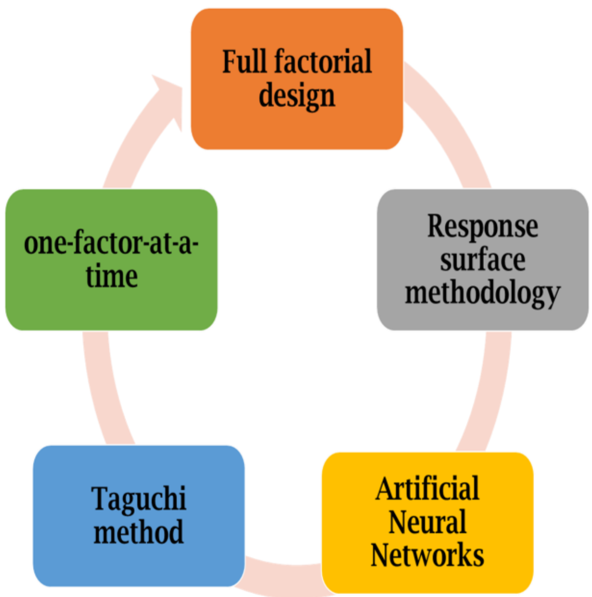

Figure 4: Common used Design of experiment [25].

variability in input parameters. It utilizes orthogonal arrays to minimize the number of experimental runs while assessing multiple factors concurrently. For example, a Taguchi L9 array (3 factors at 3 levels each) reduces trials from 27 (full factorial design) to just 9. The method employs signal-to-noise (S/N) ratios to measure the influence of each parameter on target properties (e.g., tensile strength, impact resistance), where a higher S/N ratio signifies greater resilience against external disturbances (e.g., humidity, temperature) [25].

In NFRPC research, Taguchi methods are frequently applied to optimize using some factors such as fiber treatment variables, NaOH concentration, immersion duration, and temperature. Other factors that are frequently used include reinforcement proportions, ratios of fiber-to-matrix and fiber-to-filler, curing temperature, pressure, and cycle time. For instance, Ahmad, et al. [26] applied a Taguchi L16 array to optimize banana-sisal hybrid composites, identifying 30 wt% fiber loading and 6% NaOH treatment as ideal for achieving peak tensile strength (72 MPa). Similarly, Oyewo [27] used Taguchi to establish that a 5% NaOH treatment for 6 hours and 25 wt% banana fiber content maximized flexural performance in epoxy composites.

B. Comparison with Alternative Optimization Approaches

i. Response surface methodology

RSM employs polynomial models to map variable interactions and predict optimal conditions. Unlike Taguchi, it captures non-linear relationships and identifies global optima. For example, Gao, et al. [28] used RSM to optimize oil palm fiber/seashell epoxy composites, developing a quadratic model with 95% accuracy in predicting tensile strength. While RSM offers detailed insights, it demands more experiments than Taguchi.

ii. Full factorial design

Taguchi optimization offers notable advantages over traditional factorial methods, particularly in scenarios prioritizing efficiency, robustness, and real-world applicability. While factorial designs require exhaustive testing of all factor combinations—leading to exponential growth in experimental runs as variables increase—Taguchi employs orthogonal arrays to systematically evaluate main effects and interactions with a fraction of the runs, drastically reducing time, cost, and resource consumption. This makes Taguchi ideal for industries like manufacturing, where physical experiments are expensive or time-sensitive. Taguchi's emphasis on robust parameter design further distinguishes it: by incorporating noise variables (e.g., environmental fluctuations) and optimizing the signal-to-noise (S/N) ratio, it ensures solutions remain stable under unpredictable conditions, whereas factorial methods focus primarily on identifying factor effects without explicitly addressing variability. Additionally, Taguchi simplifies decision-making by prioritizing practical, near-optimal settings over exhaustive interaction analysis, which can become unwieldy in high-factor systems. For resource-constrained environments or applications demanding quality-by-design (e.g., process engineering), Taguchi's streamlined approach balances statistical rigor with actionable, cost-effective outcomes, making it superior to factorial methods when robustness and efficiency outweigh the need for granular interaction insights [25].

iii. Artificial neural networks

Taguchi optimization offers distinct advantages over artificial neural networks (ANN) in scenarios prioritizing robustness, cost-efficiency, and interpretability. Unlike ANNs, which rely on large datasets and computational complexity to model non-linear relationships, Taguchi methods employ structured orthogonal arrays to systematically evaluate factors and interactions with minimal experimental runs, significantly reducing time and resource expenditure. This makes Taguchi particularly advantageous in manufacturing and engineering contexts where physical experiments are costly or time-consuming. Taguchi's focus on robust parameter design ensures solutions are resilient to noise variables (e.g., environmental fluctuations or material inconsistencies), a critical edge in real-world applications where ANN models might over fit to training data or struggle with variability. Additionally, Taguchi's results are inherently interpretable, providing clear insights into factor effects and optimal settings, whereas ANNs often act as "black boxes," complicating root-cause analysis. While ANNs excel in pattern recognition and adaptive learning for complex systems, Taguchi's simplicity, scalability, and emphasis on quality-by-design make it preferable for early-stage process optimization, especially when historical data is sparse or experimentation is constrained. Together, these strengths position Taguchi as a pragmatic choice for industries prioritizing reliability, cost control, and actionable insights over predictive complexity [29].

C. Challenges in the Design of Experiments

The design of experiments faces several challenges in modern applications, particularly as systems grow more complex and interdisciplinary. One primary challenge is managing high-dimensional data and multifactor interactions. Traditional factorial or fractional factorial designs struggle to efficiently explore systems with numerous variables, interactions, or responses, leading to combinatorial explosion. For example, in fields like genomics or materials science, experiments may involve hundreds of factors, making it computationally expensive to identify significant effects without overfitting. Additionally, resource constraints (e.g., time, cost, or sample availability) limit the feasibility of exhaustive testing, forcing practitioners to prioritize factors or adopt suboptimal designs. In clinical trials or industrial processes, ethical or operational restrictions further complicate randomization and replication, potentially biasing results [30].

Another challenge arises from dynamic or non-linear systems, where relationships between variables evolve over time or exhibit unpredictable behavior. Static DoE frameworks may fail to capture temporal dependencies or adaptive responses, such as in ecological studies or real-time process optimization. Reproducibility and variability also pose hurdles, especially in fields like biology or social sciences, where uncontrollable external factors (e.g., environmental conditions or human behavior) introduce noise. This necessitates robust designs that account for heterogeneity while maintaining statistical power. Furthermore, interdisciplinary collaboration introduces communication gaps; domain experts may lack statistical training, while statisticians may misunderstand contextual nuances, leading to misaligned experimental goals [31].

D. Emerging Trends in DoE

Recent advancements aim to address these challenges through innovative methodologies and technologies. A key trend is the integration of machine learning (ML) and artificial intelligence (AI) with DoE. ML algorithms enhance factor screening, optimize design spaces, and model complex interactions, particularly in high-dimensional settings. For instance, Bayesian optimization and active learning enable sequential experimentation, where data from initial trials inform subsequent rounds, reducing resource waste. Similarly, AI-driven surrogate models accelerate simulations in fields like drug discovery or aerospace engineering, bypassing costly physical experiments [25]. Another trend is the rise of adaptive and sequential experimental designs, which dynamically adjust parameters based on real-time data. This is critical in personalized medicine, where patient responses guide dose adjustments, or in industrial IoT systems, where sensors provide continuous feedback for process optimization. Digital twins—virtual replicas of physical systems—are also gaining traction, allowing researchers to simulate experiments and predict outcomes before deploying physical trials, thereby reducing risks and costs [32]. Sustainability-driven DoE is emerging as a priority, particularly in manufacturing and environmental science. Green DoE emphasizes minimizing waste, energy use, and environmental impact by optimizing resource allocation or prioritizing eco-friendly materials. Additionally, open-source platforms and collaborative tools (e.g., R, Python libraries, or cloud-based platforms) democratize access to advanced DoE techniques, fostering cross-disciplinary innovation. Finally, Bayesian methods are increasingly adopted for their ability to incorporate prior knowledge and handle uncertainty, making them ideal for small-sample studies or rare-event analysis. In fields like precision agriculture or quantum computing, Bayesian frameworks improve decision-making under ambiguity. Meanwhile, personalized experimentation—tailoring designs to individual characteristics—is reshaping healthcare and marketing, where heterogeneity demands customized approaches. As DoE evolves, these trends highlight a shift toward agility, sustainability, and integration with cutting-edge technologies, enabling researchers to tackle increasingly complex, real-world problems with greater precision and efficiency [33].

IV. Applications of Optimisation Technique to Composite Materials

Composite materials, characterized by their heterogeneous structure combining two or more constituents, offer unparalleled advantages in strength-to-weight ratios, corrosion resistance, and design flexibility. However, their anisotropic nature and complex microstructure pose significant challenges in design and manufacturing. Optimization techniques have thus become indispensable in tailoring composites to meet specific performance, cost, and sustainability goals, as evidenced by extensive literature across engineering disciplines [32].

A. Topology and Shape Optimization

Topology optimization, a computational method that determines optimal material distribution within a design space, is widely applied to composites. For instance, in aerospace, this technique minimizes weight while maintaining structural integrity under aerodynamic loads. Studies highlight its use in redistributing carbon fiber layers in aircraft wings to enhance load-bearing capacity. Shape optimization further refines component contours, such as optimizing wind turbine blade profiles to reduce stress concentrations, leveraging finite element analysis (FEA) for iterative simulations [34].

B. Material and Layup Design

At the micro-scale, optimization focuses on fiber orientation, volume fraction, and matrix selection. Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) are employed to solve non-linear problems, such as maximizing tensile strength by optimizing fiber angles in laminated composites. Research demonstrates GAs effectively balancing trade-offs between stiffness and impact resistance in automotive panels. Response Surface Methodology (RSM) aids in experimental design, identifying optimal curing parameters to reduce residual stresses during manufacturing [35].

C. Multiscale and Multi-Objective Challenges

Composites require multiscale optimization, addressing hierarchical structures from microfibers to macro-components. Micro-scale models optimize interfacial bonding between fibers and matrix, while macro-scale models adjust global geometry. Multi-objective optimization, utilizing Pareto fronts, resolves conflicting goals like cost minimization and performance maximization. A notable example is the Pareto-based optimization of bicycle frames, where weight reduction and vibration damping are simultaneously enhanced [32].

D. Manufacturing Process Optimization

Optimization extends to manufacturing, where automated fiber placement (AFP) machines are programmed for optimal layup sequences, minimizing material waste. Cure cycle optimization using gradient-based methods ensures uniform polymerization in epoxy resins, reducing defects. Literature cites case studies in aerospace where such techniques shorten production timelines by 20%, enhancing economic viability [36].

E. Industrial Applications

The characterization and optimization of cassava cortex and cow bone-reinforced polymer composite have significant implications for various industrial applications. One of the primary applications of this composite is in the production of biodegradable packaging materials. The use of cassava cortex and cow bone as reinforcement materials in polymer composites provides a sustainable and environmentally friendly alternative to traditional packaging materials. The biodegradable nature of the composite makes it an attractive option for companies looking to reduce their environmental footprint. Additionally, the composite's unique properties, such as its high strength-to-weight ratio and resistance to moisture, make it an ideal material for packaging applications [36].

According to Gaddam, et al. [37], other significant industrial application of cassava cortex and cow bone-reinforced polymer composite is in the automotive industry. The composite's high strength, low weight, and resistance to corrosion make it an attractive material for the production of automotive components, such as dashboards, door panels, and seat components. The use of this composite in automotive applications can help reduce vehicle weight, improve fuel efficiency, and minimize environmental impact. Furthermore, the biodegradable nature of the composite makes it an attractive option for companies looking to reduce waste and promote sustainability in the automotive industry.

The construction industry is another significant sector that can benefit from the characterization and optimization of cassava cortex and cow bone-reinforced polymer composite. The composite's high strength, durability, and resistance to moisture make it an ideal material for the production of building components, such as roofing materials, wall panels, and flooring materials. The use of this composite in construction applications can help reduce building costs, improve energy efficiency, and promote sustainability in the construction industry. Additionally, the biodegradable nature of the composite makes it an attractive option for companies looking to reduce waste and minimize environmental impact [13].

The aerospace industry is also a potential sector that can benefit from the characterization and optimization of cassava cortex and cow bone-reinforced polymer composite. The composite's high strength-to-weight ratio, resistance to corrosion, and biodegradable nature make it an attractive material for the production of aircraft components, such as fuselage, wings, and control surfaces. The use of this composite in aerospace applications can help reduce aircraft weight, improve fuel efficiency, and minimize environmental impact. Furthermore, the biodegradable nature of the composite makes it an attractive option for companies looking to reduce waste and promote sustainability in the aerospace industry [38].

In addition to these industries, the characterization and optimization of cassava cortex and cow bone-reinforced polymer composite also have significant implications for the medical industry. The composite's biocompatibility, biodegradability, and unique properties make it an attractive material for the production of medical implants, such as bone grafts, tissue engineering scaffolds, and wound dressings. The use of this composite in medical applications can help promote tissue regeneration, improve wound healing, and minimize the risk of complications [38].

In conclusion, the characterization and optimization of cassava cortex and cow bone-reinforced polymer composite have significant implications for various industrial applications, including packaging, automotive, construction, aerospace, and medical industries. The composite's unique properties, such as its high strength-to-weight ratio, biodegradability, and resistance to moisture, make it an attractive material for a wide range of applications. As research and development continue to advance, it is likely that this composite will play an increasingly important role in promoting sustainability, reducing waste, and improving performance in various industries. [39].

F. **Future Directions**

The future directions for the characterization and optimization of cassava cortex and cow bone-reinforced polymer composite are promising and varied. One potential direction is scalability and commercialization. Future research should focus on scaling up the production of cassava cortex and cow bone-reinforced polymer composite to make it commercially viable. This could involve developing new manufacturing processes, improving existing ones, and reducing costs. Another direction is the development of hybrid composites that combine cassava cortex and cow bone with other sustainable materials. This could lead to the development of new materials with improved properties, such as strength, toughness, and thermal resistance.

Investigating the potential of nanocomposites based on cassava cortex and cow bone is another exciting direction. Nanocomposites have the potential to exhibit improved mechanical, thermal, and barrier properties compared to traditional composites. Additionally, biodegradation studies and life cycle assessments of cassava cortex and cow bone-reinforced polymer composite could provide valuable insights into its environmental impact and sustainability. These studies could help identify areas for improvement and optimize the composite's performance.

To fully realize the potential of cassava cortex and cow bone-reinforced polymer composite, several recommendations should be considered. Standardizing the production process and characterization methods for cassava cortex and cow bone-reinforced polymer composite could facilitate comparison and benchmarking of different formulations. Collaboration between academia, industry, and government is also essential for advancing the development and commercialization of cassava cortex and cow bone-reinforced polymer composite. Establishing a regulatory framework that supports the development and use of sustainable materials like cassava cortex and cow bone-reinforced polymer composite could also help drive adoption and growth.

Raising public awareness about the benefits and potential applications of cassava cortex and cow bone-reinforced polymer composite could help build demand and drive market growth. Securing funding for research and development of cassava cortex and cow bone-reinforced polymer composite could also help accelerate progress and drive innovation in this field. Furthermore, developing education and training programs for professionals and students could help build capacity and expertise in the development and application of sustainable materials like cassava cortex and cow bone-reinforced polymer composite.

V. Conclusions

This review has provided a comprehensive overview of the characterisation and optimisation of cassava cortex and cow bone-reinforced polymer composites, highlighting their potential as sustainable and eco-friendly materials. The analysis has shown that these composites exhibit promising physical, mechanical, thermal, and morphological properties, making them suitable for various industrial applications. Furthermore, optimisation techniques such as chemical treatment, coupling agents, and hybridisation have been identified as effective methods to enhance the properties of these composites. While challenges still exist, particularly in terms of scalability and standardisation, the development of cassava cortex and cow bone-reinforced polymer composites presents a significant opportunity for the creation of more sustainable and environmentally friendly products. Future research should focus on addressing the existing challenges, exploring new applications, and developing innovative manufacturing techniques to fully realise the potential of these sustainable materials.

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