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A NATURAL FIBER-REINFORCED COMPOSITES: A COMPREHENSIVE REVIEW OF MATERIALS, METHODS, AND APPLICATIONS

Gangu Vardhan, IV/IV B. Tech student Mechanical Engineering Dept, NRI Institute of Technology, Eluru, Andhra Pradesh
Chinthakayala Teja, IV/IV B. Tech student Mechanical Engineering Dept, NRI Institute of Technology, Eluru, Andhra Pradesh
Oleti Uday kumar, IV/IV B. Tech student Mechanical Engineering Dept, NRI Institute of Technology, Eluru, Andhra Pradesh
Dr. K. Babu Raja, Associate Professor in Mechanical Engineering Dept, NRI Institute of Technology

ABSTRACT
Natural fiber-reinforced composites (NFRCs) are rapidly gaining attention due to their eco-friendly, renewable, and biodegradable characteristics. These composites utilize fibers such as jute, hemp, flax, sisal, and coir embedded in polymer matrices, making them promising for sustainable material development. The review covers an exploration of mechanical, thermal, acoustic, and biodegradable properties, addressing factors like fiber treatment, alignment, and hybridization. While NFRCs offer clear environmental benefits, the review also highlights ongoing challenges like moisture sensitivity and weak fiber-matrix adhesion. Recent innovations—such as advanced surface treatments, integration of nanomaterials, and the use of bio-resins—aim to enhance NFRC performance for wider applications in industry.

Keywords:
Natural fibers, composites, industrial applications, Mechanical properties.

I. Introduction
Natural fiber-reinforced composites (NFRCs) are growing in popularity as eco-friendly alternatives to synthetic fiber composites. When embedded in a polymer matrix, these fibers impart sustainability advantages, such as renewability and biodegradability, making NFRCs attractive for environmental conservation. NFRCs find uses across a range of industries including automotive, construction, packaging, and consumer goods, due to their favorable strength, thermal stability, and acoustic performance. The performance of these composites is strongly influenced by the methods of fiber treatment and orientation, as well as the hybridization of different fibers. Weak bonding between fiber and matrix poses durability challenges, prompting ongoing advancements in surface modification, nanotechnology, and bio-based resin selection. Continuous research is dedicated to improving scalability, durability, and mainstream industrial integration of these green composite materials.

II. Literature
Sustainable composites using recycled polyethylene terephthalate (rPET) matrices and natural fibers as reinforcements, emphasizing their environmental benefits and mechanical properties. Key topics include classification, composition, and surface modification of natural fibers to enhance interfacial bonding, along with challenges related to moisture absorption and compatibility. Studies cited demonstrate improved mechanical behavior with surface treatments and highlight application areas, advantages, and limitations of natural fiber-reinforced rPET composites[1]. Natural fiber-reinforced epoxy composites are emerging as sustainable alternatives to synthetic composites due to their renewable origin, biodegradability, and favorable mechanical properties. Various natural fibers like jute, flax, hemp, and sisal, when combined with epoxy matrices, enhance tensile strength, flexural modulus, and impact resistance. These composites find applications in automotive, aerospace, construction, and household sectors owing to their lightweight, cost-effectiveness, and eco-

friendliness. Challenges include moisture absorption, interfacial bonding, and variability in fiber properties. Ongoing research aims to improve durability, processing methods, and recycling to support sustainable industrial adoption [2]. Natural fibers such as jute, hemp, and flax for making polymer composites due to their renewability, low density, and good mechanical properties. Prior studies showed that fiber-matrix adhesion and fiber treatments significantly influence mechanical performance, including tensile, flexural, and impact properties. Hybridization, chemical modification, fiber loading, and orientation were examined to optimize properties, and SEM analyses revealed that fiber-matrix interface quality is critical for composite strength and durability[3]. Natural fiber-reinforced polymer composites have gained attention due to their eco-friendliness, lightweight, and good mechanical properties, finding applications in automotive, aerospace, and structural fields. Jute, hemp, and flax fibers exhibit promising mechanical traits and are increasingly used in hybrid composites, which often improve strength and wear resistance. Tribological performance depends on fiber type, orientation, and surface treatment. Woven fabrics enhance wear resistance by limiting fiber pull-out. Dynamic mechanical analysis (DMA) helps assess viscoelastic behavior and interfacial bonding, crucial for composite performance and durability under load and temperature variations[4]. Nanocelluloses (NCs) in fiber-reinforced cement composites, highlighting their potential to enhance mechanical properties, rheology, and durability due to high surface area and strong fiber–matrix interactions. It discusses production methods, types (CNFs, CNCs, BC), and application strategies, such as reinforcing raw materials, additives, and surface treatments. The review also identifies factors affecting NC efficiency and challenges like cost, dispersion, and scalability, proposing future research on new applications and sustainability[5]. Naturalfiber-reinforced epoxy composites as eco-friendly alternatives to synthetic materials. It discusses the synthesis methods involving bio-based resins and natural fibers like jute, hemp, flax, and sisal, emphasizing their mechanical enhancements and biodegradability. These composites show promise in automotive, aerospace, and construction applications due to their lightweight, renewable nature, and improved mechanical and thermal properties. Challenges such as moisture absorption, interfacial bonding, and processing are noted, with ongoing research focusing on durability, surface treatments, and sustainable manufacturing[6]. The potential of natural fiber-reinforced polymer composites as eco-friendly alternatives to synthetic materials. It covers various natural fibers like jute, hemp, flax, and sisal, emphasizing their renewable, biodegradable nature and mechanical benefits. The review discusses fiber extraction, surface treatments to improve interfacial adhesion, and fabrication techniques such as compression and injection molding. Challenges include moisture absorption and durability, with future research focusing on enhancing performance and expanding applications in automotive, construction, and engineering sectors[7]. The mechanical and acoustical properties of natural fiber-reinforced composites, highlighting their environmental benefits, cost-effectiveness, and strong mechanical and sound-absorbing capabilities. It covers key testing methods and critical parameters—such as fiber properties, binder content, and thickness—that influence performance. The study notes the wide range of strengths and sound absorption across different composites and emphasizes optimizing these parameters for best results in applications like construction, automotive, and acoustical insulation[8]. Natural fiber-reinforced composites, emphasizing materials like jute, cotton, and glass fibers blended with polyester resin for low-cost, durable building products. Past research demonstrated that hybrid composites offer benefits such as reduced weight, improved strength, and durability, particularly in rural housing and roofing. Studies also highlight the importance of fiber combinations, fabric structures, and processing methods in achieving desired mechanical and physical properties, making these composites viable alternatives to conventional materials[9]. The antibacterial properties of hemp and other natural fiber plants such as jute, flax, kenaf, sisal, bamboo, and banana. It highlights hemp's potent antibacterial activity attributed to compounds like cannabinoids, alkaloids, and phenolic lignin components. Various extracts from different plant parts demonstrate inhibition against a wide range of pathogens. The review underscores hemp's potential in diverse applications, including polymer composites, biomedical products, and food packaging, encouraging further exploration for valueadded antibacterial material development[10].The renewed interest in hemp fiber as a natural reinforcement in polymer composites due to its superior mechanical properties, sustainability, and cost-effectiveness. It covers hemp fiber structure, chemical and physical surface modification methods to improve fiber-matrix adhesion, and various fabrication techniques for thermoplastic and thermoset composites. The review also discusses the potential of hemp hybrid composites with other fibers, emphasizing their enhanced mechanical performance and eco-friendly nature, positioning hemp fiber composites as promising materials for automotive, construction, and consumer goods applications[11]. The fibre volume fraction on the mechanical properties of hemp fibre woven fabric polypropylene (PP) composite laminates. Previous research has shown natural fibre composites are favored for their biodegradability, low density, and mechanical properties. Increasing fibre content generally enhances tensile strength, modulus, and stiffness up to an optimal point, beyond which properties may decline due to poor fibre-matrix adhesion. Research emphasizes fibre fraction's critical role in composite performance, impacting tensile, flexural, and dynamic behavior in automotive and engineering applications[12]. Natural fiber-reinforced composites (NFRCs) emphasizing their environmental benefits, mechanical properties, and usage in structural applications. NFRCs offer advantages such as lightweight, biodegradability, and cost-effectiveness but face challenges related to moisture absorption, variability in fiber properties, fiber-matrix adhesion, and thermal stability. Despite limited use in high-load applications, NFRCs have promising potential for automotive, construction, and infrastructure sectors. Improving fiber treatments, understanding interface mechanics, and developing standards are critical for wider adoption[13]. Hollow glass microspheres (HGM) on continuous natural fiber (jute, hemp, flax) reinforced polypropylene (PP) composites. Incorporation of 1.5% HGM improved tensile and flexural properties, while 3% HGM led to property decline due to filler agglomeration. All composites showed enhanced impact strength with HGM addition. The results highlight that low HGM content optimizes mechanical performance through improved load transfer and matrix-fiber interaction, positioning HGM as promising fillers to enhance natural fiber composites for automotive and aerospace applications.[14]. Eco-friendly hybrid composites combining natural fibers such as jute and hemp with polymer matrices. Jute and hemp fibers offer biodegradability, cost-effectiveness, and promising mechanical properties, though challenges include variability and moisture absorption. Hybridization of natural fibers improves strength, stiffness, and durability compared to single fiber composites. Applications span automotive, construction, and packaging industries. Surface treatments like alkaline treatment enhance fiber-matrix adhesion. Despite advancements, further research is needed to optimize processing, performance, and long-term durability of natural fiber-based hybrid composites[15]. Mechanical enhancement of hemp fiber reinforced epoxy composites through graphene nanoparticle (GnP) incorporation. Natural fibers like hemp offer eco-friendly, lightweight alternatives to synthetics but suffer from lower strength and moisture absorption. GnPs improve tensile, flexural, and impact properties by enhancing fiber-matrix bonding and load transfer, with 2 wt% GnP identified as optimal. These findings highlight the potential of nanofiller hybridization to optimize natural fiber composites for structural applications[16]. Natural fibre reinforced composites (NFRCs) are increasingly favored for their biodegradability, renewability, and eco-friendliness as alternatives to synthetic fibers. Plant-based fibres like jute, hemp, flax, and sisal offer good mechanical properties but face challenges such as poor fibre-matrix adhesion, moisture absorption, and thermal instability. Various chemical and physical fibre treatments improve wettability and interfacial bonding, enhancing composite performance. NFRCs are widely used in automotive, construction, and packaging industries, with ongoing research focusing on fabrication methods, property optimization, and sustainability[17]. Natural fiber-reinforced composites (NFRCs) are gaining attention for applications in automotive, aerospace, marine, and construction sectors due to their biodegradability, low cost, and mechanical benefits like high strength and light weight. Challenges include poor fiber-matrix adhesion, high moisture absorption, and low thermal stability of natural fibers. Chemical treatments and fiber surface modifications enhance interfacial bonding and performance. NFRCs show promise in structural applications such as beams, roofs, and bridges, supported by sustainable manufacturing developments and emerging bio-based composites.[18]. Fabric architecture and γ-radiation on the mechanical properties of jute fiber-reinforced polyester composites. Various woven architectures (plain, twill variants) influence fiber alignment, crimp, and resin impregnation, affecting composite strength. The 3/1 twill weave yields superior tensile, flexural, and impact properties due to optimized fiber orientation and reduced crimp. γ-Radiation (optimal dose ~5 kGy) further enhances mechanical properties by inducing crosslinking between fibers and matrix, while reducing moisture absorption, thus improving composite durability and load capacity[19]. Natural fiber-reinforced composites, particularly jute/polyester composites, have gained prominence due to their biodegradability, low cost, and mechanical benefits like high strength and stiffness. Surface chemical treatments (e.g., NaOH, NaHCO3, Cr2SO4) improve fiber-matrix compatibility, enhancing mechanical, vibration damping, and acoustic properties. Modified composites, especially with sodium bicarbonate treatment, show superior natural frequency and sound absorption, making them suitable for sustainable structural and noise-reducing applications[20]. Coir fiber-reinforced bio composites due to their renewable, biodegradable, and sustainable nature. Coir fibers, derived from coconut husks, offer superior mechanical, thermal, and physical properties compared to synthetic fibers, with enhanced durability from high lignin content. Surface treatments improve fiber-matrix adhesion, optimizing composite strength, flexural, and impact performance. Coir composites find applications in automotive, construction, ballistic protection, and consumer products. Various fabrication methods and challenges like fiber variability and environmental impacts of retting are discussed, emphasizing coir's growing market potential [21]. Sisal fiber reinforced polyethylene terephthalate (PET) composites fabricated by compounding and injection molding. It demonstrates that incorporating 40 wt.% sisal fibers improves PET's tensile modulus by up to 233% when fibers are alkali and acetylation treated. Although thermal degradation of fibers occurs during processing, treated fibers enhance interfacial adhesion, mechanical, thermal, and water resistance properties. The composites outperform conventional PP-based composites used in automotive interiors, indicating PET-sisal composites' potential for lightweight, eco-friendly automotive applications [22]. Previous research demonstrated improvements in tensile, flexural, and impact properties with treated coir fibers in polyester and epoxy matrices. Surface treatments such as NaOH enhance fiber-matrix bonding, increasing strength and machinability. Mechanical testing confirmed that higher fiber content improves impact and flexural strength up to an optimal 70% coir content, supporting its application in protective helmets [23]. The mechanical properties and applications of coir fiber-reinforced composites, emphasizing their eco-friendly, lightweight, and durable nature. Coir fiber, extracted from coconut husk, enhances the tensile, flexural, and impact strengths of epoxy composites up to an optimal content (8–10 wt.%), after which properties decline due to poor fiber-matrix bonding. Applications discussed span automotive, construction, ballistic protection, and industrial uses, highlighting coir composites as sustainable alternatives to synthetic materials in engineering applications[24]. Sisal fiber-reinforced green polyethylene composites produced via hot compression moulding, emphasizing sustainable material development through using renewable polymers and natural fibers. Sisal fibers, arranged in woven and random configurations, enhance mechanical properties like tensile strength and modulus compared to pure polyethylene. Woven fibers show better tensile strength due to alignment, while random fibers offer increased stiffness. These eco-friendly composites demonstrate potential for structural applications such as insulation and automotive interiors, aligning with environmental goals of biodegradability and resource efficiency [25]. Plant fibers as sustainable materials increasingly used in construction composites due to their low cost, biodegradability, and mechanical properties comparable to synthetic fibers. Common fibers like coir, hemp, jute, sisal, and flax enhance the strength and flexural performance of cementitious composites. However, their high moisture absorption and poor fiber-matrix adhesion limit durability, addressed by chemical treatments such as alkali and acetylation. Plant-fiber-reinforced composites offer eco-friendly alternatives for structural and non-structural applications, supporting sustainable development goals[26]. Green composites using recycled polyethylene from sugarcane ethanol and sisal fibers, processed via hot compression molding. Woven sisal fibers in (0°/90°) orientation enhance tensile strength and ductility compared to randomly arranged fibers, which impart greater stiffness. Green HDPE composites outperform traditional HDPE in mechanical properties, indicating suitability for structural applications like drywall and insulation. The eco-friendly manufacturing method promotes sustainability by utilizing renewable resources without chemical fiber treatment, supporting circular economy and environmental goals [27]. Hybrid natural fiber-reinforced polymer composites (NFRCs), emphasizing their eco-friendly nature, low cost, and industrial potential despite lower mechanical properties compared to synthetic fibers. Hybridization with synthetic or other natural fibers improves mechanical, thermal, and moisture resistance properties. Challenges include fiber-matrix adhesion, moisture absorption, and thermal stability, addressed through surface treatments and optimized stacking sequences. Applications span automotive, aerospace, and ballistic uses, driven by growing demand for sustainable, lightweight materials with enhanced performance[28]. Natural fiber-reinforced epoxy composites (NFRCs) highlighting their eco-friendly, lightweight, and cost-effective features for construction and automotive uses. Challenges like moisture absorption and fiber-matrix adhesion are addressed via chemical and physical fiber treatments, enhancing mechanical, thermal, and physical properties. Mechanical strength improves with optimal fiber content, orientation, and surface modification. NFRCs show promise in structural applications due to biodegradability, corrosion resistance, and good impact performance. Continued research targets overcoming limitations for wider industrial adoption and sustainability[29]. Natural fiber-reinforced polymer composites (NFRPCs) emphasizing their eco-friendly, biodegradable nature and cost-effectiveness compared to synthetic fibers. It highlights the challenges of fiber-matrix adhesion, moisture absorption, and mechanical property variability, which are addressed through various chemical and physical fiber surface treatments like alkali, silane, and benzoylation. Manufacturing techniques and hybridization with synthetic fibers improve performance. NFRPCs have growing applications in automotive, construction, and sports industries due to their lightweight, sustainability, and mechanical benefits. Future research focuses on enhancing durability and large-scale production[30]. The effects of alkali treatment on kenaf fibers and kenaf/epoxy composites, revealing that 6% NaOH treatment cleans fiber surfaces and enhances thermal stability but reduces tensile strength and Young's modulus due to fiber damage and void formation. Untreated kenaf fibers showed superior mechanical properties when reinforced in epoxy composites. Mechanical performance declines with temperature rise, especially in untreated composites. Overall, kenaf fibers are promising reinforcements, but optimal treatment conditions are vital to avoid compromising strength [31]. Optimized hybrid formulations improve tensile, flexural, and impact strength, with Sisal enhancing mechanical performance, Kapok providing superior sound absorption, and Palm enhancing thermal insulation. Compression molding ensures uniform fiber distribution and matrix bonding. Results demonstrate trade-offs between mechanical strength and acoustic/thermal performance, highlighting potential applications in automotive and building industries for sustainable, multifunctional materials with balanced structural and insulation properties[32]. Polyethylene-based composites reinforced with jute fibers and magnetite filler, demonstrating enhanced mechanical properties such as tensile strength, flexural modulus, and impact resistance. Alkali treatment of jute fibers improves fiber-matrix adhesion, reducing water uptake and increasing durability. These composites show promise for radiation shielding and eco-friendly applications due to their lightweight, biodegradability, and cost-effectiveness compared to synthetic fibers. Compression molding is proven effective for fabricating uniform composites with balanced mechanical strength and environmental benefits[33]. Natural fiber reinforced composites (NFCs) for sandwich structure applications due to their sustainability, low weight, and good mechanical properties. Despite challenges like moisture absorption and poor fiber-matrix adhesion, treatments such as alkali and hybridization improve performance. Various core designs, including cellular foams, corrugated, and honeycomb, enhance energy absorption and stiffness. NFC sandwich structures demonstrate promising mechanical and impact resistance, with hybrid fiber composites showing superior strength and energy absorption, indicating potential for diverse industrial uses. Further research on NFC sandwich structures is recommended [34]. The development of natural fiber reinforced polymer composites (NFRPCs) in product design, highlighting their environmental benefits, renewability, and comparable mechanical properties to synthetics. Despite drawbacks like moisture absorption and lower fire resistance, treatments and hybridization improve performance. NFRPCs are increasingly applied across industries including automotive, electronics, packaging, and sports. Integrated design processes involving sustainability, customer input, and inventive problem-solving enhance product functionality. Continued research on design optimization and manufacturing is essential for expanding natural fiber composites' industrial applications [35]. Coconut fibers in cement composites, emphasizing their sustainability, low density, and ability to improve concrete's mechanical properties such as tensile, flexural, and impact resistance. Coconut fibers reduce cracking and increase durability but face challenges like fiber variability and moisture sensitivity. Treatments like alkali improve fiber-matrix adhesion and durability. Textile meshes with coconut fibers show promise for reinforcement. Further research is needed on durability, treatment methods, and applications in various cementitious materials [36]. Natural lignocellulosic fibers as sustainable, low-cost reinforcements for cementitious composites, improving crack resistance, durability, and mechanical properties. Brazilian fibers like coconut, sisal, açai, and pineapple show promise due to favorablecellulose content and mechanical performance. Fiber-matrix adhesion, fiber geometry, and surface treatments (especially chemical alkaline treatments) are crucial for enhancing composite strength and durability. Optimal fiber content ranges from 3% to 5% by weight to balance workability and performance. Further research is needed on treatment methods and single fiber optimization [37]. Epoxy composites reinforced with natural powders from olive and date seeds, focusing on tensile and impact properties. Olive seed powder at 18 wt% and 300 µm particle size notably enhances modulus of elasticity and tensile strength, though elongation at break and impact strength decrease with increased powder content. Mathematical modeling shows weight fraction has a greater influence on composite properties than particle size. These findings demonstrate the potential of lignocellulosic seed powders as eco-friendly, effective fillers to improve polymer composite performance [38]. Fiber-reinforced polymers (FRPs) as advanced, durable, and lightweight materials extensively used in structural design for retrofitting, seismic strengthening, and new construction. It discusses various FRP types—carbon, glass, aramid, and basalt—emphasizing their mechanical properties, bond behavior, and failure modes. Recent innovations include nano-enhancements and hybrid fiber systems, improving performance and sustainability. Challenges such as durability, bond quality, cost, fire resistance, and standardization are addressed, with future research focusing on eco-friendly materials, advanced bonding, and comprehensive design protocols [39]. Pineapple leaf fiber (PALF)-reinforced epoxy composites enhanced with fly ash (FA) filler for biomedical applications. Incorporating up to 6 wt% FA significantly improves tensile strength by 65.3% and flexural strength by 31.9%, while impact resistance peaks at 9 wt% FA with a 74.18% increase. Water absorption decreases with higher FA content, indicating enhanced durability. Optimal composites contain ~20 wt% PALF and ~6 wt% FA, showcasing eco-friendly, mechanically robust materials suitable for biomedical use [40].

III. Conclusion

The following conclusions are drawn from the review Natural fiber composites are becoming a strong and eco-friendly alternative to synthetic materials. Researchers are using fibers like jute, hemp, and flax—either alone or in combination—to make materials that are lightweight, biodegradable, and have good strength. By adding things like epoxy resin or nanoparticles (like graphene), these composites become even stronger and more durable. The testing shows that hybrid combinations (mixing different fibers) often perform better than single-fiber materials. These natural fiber composites are useful in industries like construction, automobiles, packaging, and more. They help reduce environmental damage while still offering strong mechanical properties.

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