IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Sustainable Materials For A Circular Economy: Challenges And Future Directions In Biochar, Biopolymers, And Manufacturing

N Karthikeyan[1*] L.Balasubramabyam[2] M. Sowmya[3] S.Vamsi Krishna Naik[4] K. Anil Kumar[5]

1. Assitant Professor, PVKK Institute of Technology, Anantapur, India.
2. Professor, PVKK Institute of Technology, Anantapur, India.
3. IV B.Tech (Mechanical Engineering) , PVKK Institute of Technology, Anantapur, India.
4. IV B.Tech (Mechanical Engineering) , PVKK Institute of Technology, Anantapur, India.
5. IV B.Tech (Mechanical Engineering) , PVKK Institute of Technology, Anantapur, India

Abstract

Research on bio-based reinforcements primarily focuses on biochar and biopolymers because of growing demands for sustainable materials in circular economies. The review examines how biochar sourced through pyrolysis serves as an environmentally responsible substitute against traditional synthetic composites for polymer reinforcement applications. Biochar enhances biodegradable polymer composites by improving tensile strength, thermal properties, and tribology due to its high surface area as well as mechanical stability and morphological adjustability. The biochar integration helps circular economy by converting agricultural and industrial waste biomass into value-added materials thus both reducing environmental impact and improving resource efficiency. The study presents essential developments regarding biochar-polymer composites while showing their usage in construction along with packaging and additive manufacturing applications. The review also outlines hurdles including scalability and dispersion uniformity alongside processing boundaries before suggesting the future implementation of machine learning systems for material enhancement and improved recycling procedures. The research goal is to merge vital knowledge deficits and create a pathway for industrial-scale biochar-based composite adoption that leads to sustainable material development.

Keywords: Sustainable Materials, Circular economy, Biodegradable Polymers, Pyrolysis Biochar, Mechanical Properties, Tribological behaviour, Rheological Properties, Life cycle Assessment.

1. Introduction

1.1 Sustainability in Composite Materials: The ever-growing environmental concerns and scarcity of resources led to a shift in this direction for sustainable materials across almost all industries. Among them, sustainable composites seem to have emerged as one of the promising solutions to tackle specific environmental concerns. These materials exploit renewable, biodegradable, or recyclable feedstocks to lower the environmental damage throughout their life cycles. Continued development with eco-friendly reinforcements of sustainable composites promises a performance boost and environmentally-oriented projects.

Conventional composite materials usually use synthetic reinforcements such as carbon and glass fibers. Many are energy-consuming to produce, become non-biodegradable, and create significant managerial problems regarding end-of-life issues. [1]. Renewable materials such as biochar produced from the pyrolysis of biomass can replace these reinforcements with various environmental benefits. Biochar not only acts as a carbon sink by locking atmosphere carbon dioxide but also improves the mechanical, thermal, and tribological properties of polymer matrices. [2]

In addition, the production of biochar via pyrolysis complies with circular economy principles since it valorizes agricultural and industrial biomass waste into high-value materials. [3]. It reduces the dependency on virgin materials, helps in waste management, and thus resource efficiency. Contrasting with synthetic reinforcements, biochar offers unique functionalities due to its tuneable morphology, high porosity, and surface reactivity suited for specific application needs. [4].

Incorporating biochar as reinforcement towards sustainability goals assures the use of renewable feedstocks, reduction of greenhouse emissions, and enhanced biodegradability of composites. This gives biochar a green and economically sound replacement for conventional reinforcement, leading the way for greener materials for packaging, construction, and electronics. [5].

This paper opens up an avenue for critical reviews on the research gaps and opportunities around the development of sustainable composite materials on the integration of biochar and other bio-based reinforcements. This review is dedicated to addressing these gaps and consequently moving towards developing sustainable composites that facilitate a resilient and circular economy.

1.2 Pyrolysis-Generated Biochars: Pyrolysis is a thermochemical process in which organic materials are decomposed by heat without oxygen, yielding biochar, bio-oil, and syngas as their primary products. This offers an environmentally sustainable and versatile approach to converting agricultural and industrial wastes into high-value materials. Pyrolysis feedstocks typically comprise crop residues, wood waste, municipal solid waste, and industrial by-products; thus, it is a remarkable tool for waste management and resource recovery [3]. The resulting biochar is a carbon-rich material with a porous structure, Making it a viable solution for various applications.

Biochar is a renewable reinforcement, derived from pyrolysis that can be used in composite production. Carbon content and weighing in lightweight make it an order of magnitude better than traditional failrings (glass or carbon fibers). Biochar is not like these traditional reinforcements, it is essentially waste and so it is the green plus circular economy [4]. Further, making biochar from agricultural residues(such as rice husks, olive pomace, coffee grounds, etc) may be an affordable and per se eco-friendly approach how to mitigating landfill waste and greenhouse gas emissions [2].

Increased attention on biochar incorporation in polymer composites to improve mechanical, thermal, and barrier properties. Its carbonaceous nature not only aids in the strength and stiffness contribution of composites by itself, but also brings thermal stability, and fire resistance (as flame retardant applications)[6]. In addition, the unique porosity and surface chemistry of biochar opens up the possibility for functionalization, leading biochar to be used in more functional applications including energy storage, water treatment, and even eco-friendly packaging.[5].

In that light, the sustainability and potential for multiple uses of biochar demonstrate an avenue for biochar to substitute synthetic reinforcements and resolve some of the most serious environmental as well as economic problems. Consequently, biochar derived from pyrolysis is a must for advancing the preparation of green materials for packaging, construction, and electronic applications. The study here is on the characteristics and benefits of pyrolysis-derived biochar performing as reinforcement providing the possible research deficiencies for development.

1.3 Objectives of the Review: Sustainable raw materials are the focus of research, so biochar-filled composites have gained considerable attention over the past years, due to the eco-benefits, low-cost production, and multifunctional properties of biochar. Distinctive to this material, high surface area, and a variety of oxygen-capped functional groups, it is a reconfigurable material suited for other uses besides reinforcing biochar. Biochar in polymer composites is contemplated to have promising applications in terms of increasing mechanical strength, tribological behavior, and rheological properties which are needed for almost any use.

To use biochar to its full potential, we must know how biochar affects the mechanical, tribological, and rheological behavior of composite. Biochar also improves mechanical properties, ie., tensile strength and toughness. Coffee grounds (spent, back from your last cup) as a charring content on PLA composites resulted in flame retardancy improvement, and toughened was shown to be a potential biochar mechanical reinforcement [6]. Gluten-based biocomposite with biochar had significant improvements in hardness, wear, and modulus thus showing tribological advantages. [7]. Rheologically biochar composites enhance processability with a special focus on additive manufacturing where they add structural benefits and superior properties. [8].

Beyond many sectors, biochar composites have been established. As an example, the effective application of coffee waste-derived biochar as a flame retardant in epoxy nanocomposites led to a substantial decrease in heat release rate(HRR) and smoke emission. [2]. Food packaging biochar-cheditosan films showed significant enhancement in tensile strength, barrier properties, and moisture vapor-relay performance which makes them applicable for active packaging applications. [9]. Additive manufacturing and biochar application have also improved the mechanical thermal properties of biodegradable composite materials performance, to (hopefully) optimize processes for more sustainable production. [10]. While these developments have taken place, however, many challenges prevent most from utilizing biochar composites broadly. Major problems to be solved are scalability over biochar, dispersion in polymer matrices, and as a principle biochar polymers contradict each other. A combination of these factors typically restricts the biochar composites' performance in industrial-scale applications [11]. Additionally, biochar composites' long-term durability and aging resistance are still challenges that need to be solved in this area [12].

2. Background

2.1 Sustainable Composites

Biodegradable polymer composites have also attracted significant interest due to their functional properties as well as environmental benefits. Biodegradable polymers have been divided into three categories:

Polymer Matrix Composites (PMCs): These involve biodegradable polymers such as polylactic acid (PLA) as the primary matrix. PLA is a source-based renewable material and has good mechanical properties but is highly susceptible to brittleness as well as poor thermal stability[12].

Natural-Fiber-Based Composites: The addition of biochar from farm waste such as spent coffee grounds to PLA enhances Mechanical Strength, fire resistance, and thermal stability[6]. Wheat gluten and pine bark biochar also reinforce polymer matrices through mechanical interlocking[7] .

Hybrid Composites: Research demonstrates that the combination of recycled carbon fibers along with waste glass fibers to mix plastics generates durable sustainable composite materials under circular economy principles[1].

Applications

- **Automotive & Construction**: Biochar reinforcement in PLA composites strengthens the material enough for structural applications [9].
- **Packaging:** PLA-based composites with biochar show promise as food packaging material since they provide better protection against moisture and oxygen penetration[11].
- **Consumer Goods:** The combination of 3D printing techniques and biochar-reinforced biodegradable composites enables manufacturers to create sustainable customized products[8].

2.2. Pyrolysis Process:

Biochar and bio-oil along with gas products result from heating biomass through the pyrolysis method. Multiple fundamental factors determine the effectiveness of pyrolysis together with biochar attributes.

- **Temperature:** The structural quality of biochar produced from a temperature between 500–800°C improves its ability to function as a reinforcing agent in biodegradable polymers because it creates both larger pore space and higher surface area[3].
- **Residence Time:** Biochar carbonization achieves better results through extended processing although it could modify the mechanical characteristics of the biochar material[2].

- **Feedstock type:** Biochar obtained from lignocellulosic materials such as wood and coffee grounds and wheat gluten possesses exceptional thermal stability and mechanical reinforcement abilities[7].

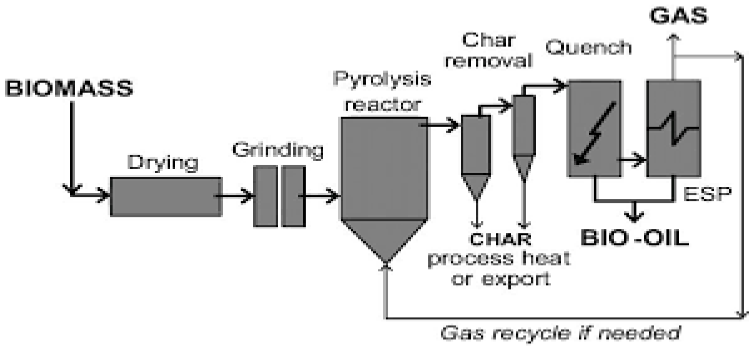

Fig1. Pyrolysis Process

Influence of Pyrolysis Conditions on Biochar Properties:

- **Chemical Composition:** By controlling the pyrolytic process researchers can increase carbon content while minimizing volatile compounds production thus improving matrix incorporation of materials[13].
- **Structural Characteristics:** Biochar generated through high-temperature pyrolysis contains more graphitic content that enhances the thermal stability of PLA-based composites[14].

2.3 Sustainability and Circular Economy

The incorporation of biochar into biodegradable polymers supports circular economy practices through dual benefits for climate and profit.

Environmental Benefits:

- **Waste Valorisation:** The utilization of spent coffee grounds, wheat gluten, and agricultural residues as biochar materials serves two purposes: it decreases organic waste and supports sustainable material progression[6] .
- **Carbon Sequestration:** Biochar functions as a carbon-storing mechanism for lowering greenhouse gas emissions that appear during plastic manufacturing processes[15].
- **Reduced Reliance on Non-Renewable Resources:** Biodegradable polymers combined with biochar result in a promising sustainable alternative for petroleum-based plastics[11].

Fig 2. Circular Economy Model

Economic Aspects:

- **Cost Effectiveness:** Biochar is an economical filling agent relative to conventional carbon black or silica fillers, making biochar-filled PLA composites an affordable option[16].
- **Resource Efficiency in Additive Manufacturing:** Biochar-reinforced PLA when used in 3D printing produces efficient material usage and enables creators to customize product shapes[8].

3. Mechanical Properties

3.1. Overview of Mechanical Properties

The mechanical properties of polymer composites excel in engineering applications because modifications in matrix materials and reinforcements and processing methods enable properties control. Polymer composites possess three main mechanical properties: tensile strength, modulus of elasticity, and fracture toughness.

- **Tensile Strength:** The tensile strength serves as an essential tool to assess how much load theoretical polymer composites can bear[17]. When exposed to tensile loading polymer materials reach their maximum stress threshold point before failure occurs. Tensile strength levels of polymer composites stem from the fiber content along with their arrangement angle and the effective bonding strength between reinforcing materials and the polymer framework[17].
- The incorporation of carbon fibers into polymers makes CFRPs achieve high tensile strength through the superior mechanical properties of these fibers.
- Tensile strength from glass fiber-reinforced polymers (GFRPs) falls in the middle range while their economic benefits excel.
- NFRPs deliver reduced tensile strength though they remain environmentally sustainable because of their natural materials.

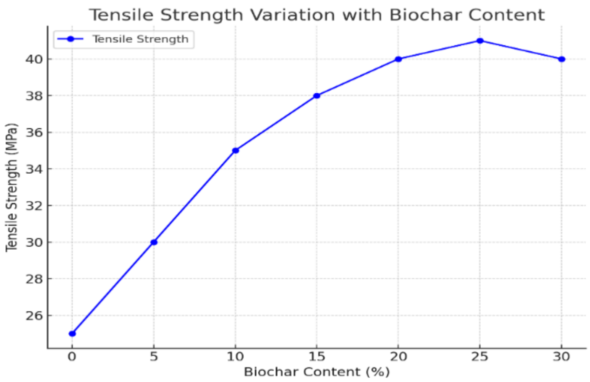

Fig 3. Tensile Strength Variation with Biochar Content

The graph illustrates the relationship between biochar content (in weight %) and the tensile strength (in MPa) of PLA composites. The key observations from the trend are

- As biochar content increases from **0% to 20%**, the tensile strength shows a significant improvement.
- This is likely due to biochar reinforcing the PLA matrix, enhancing load transfer and mechanical properties.

- The highest tensile strength (~41 MPa) is observed at **25% biochar content**, suggesting an optimal reinforcement level.
- At **30% biochar content**, the tensile strength slightly decreases (~40 MPa).
- This could be due to **biochar agglomeration**, leading to defects in the matrix and reduced stress distribution efficiency.
- **Modulus of Elasticity**: The stiffness measurement of polymer composites operates through a parameter called the modulus of elasticity which scientists call Young's modulus[18]. The material assessment through Young's modulus determines how well an applied load will deform the material structure. Higher rigidity in a polymer composite corresponds to increased values of its modulus [18], [19]. This measurement shows how a material resists changing shape when a force acts upon it. Within materials, the raised modulus demonstrates better rigidity.
- The intrinsic stiffness of carbon fibers gives CFRPs their status as polymer composites with the greatest modulus.
- Combining different fibers through hybrid composite production enables users to find optimal levels of stiffness and elasticity.
- The inclusion of nano-fillers consisting of graphene or carbon nanotubes leads to increased stiffness while producing minimal weight increase.
- **Fracture Toughness**: Materials show their fracture toughness when they fight against crack growth under stress conditions according [20]. Impact resistance together with durability represents essential structural requirements that must include crack resistance properties under stress [20], [21]. Structural applications need this property for offering resistance to impacts as well as maintenance of durability.
- Aramid fibers such as Kevlar in polymer composites lead to excellent fracture toughness through their excellent energy absorption properties.
- The introduction of ductile thermoplastic polymer matrices leads to higher fracture toughness compared to brittle thermosetting matrices.
- Surface modifications along with interfacial treatments between fibers and polymer matrix strengthen their bond which boosts toughness.

3.2 Influence of Biochars on the Mechanical Performance of Polymer Composites

Biochar functions as an effective reinforcing material for polymer composites because it improves interfacial bonds and supports load transfer and decreases material fracture.

- **Improved Interfacial Bonding:** Higher temperature processing of biochar enables the creation of extensive surface areas that improve mechanical bond formation between the biochar and polymer framework. The polymer enters the biochar pores during the molten state thus creating stronger bond interactions and mechanical properties between components[7]. The addition of volatiles in biochar produces functional groups that enhance the chemical bonding interaction between biochar and the polymer matrix[7].

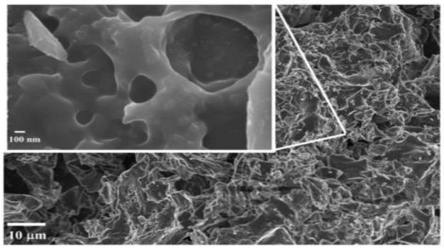

Fig 4. SEM micrograph of Coffee waste-derived Biochar composite[2]

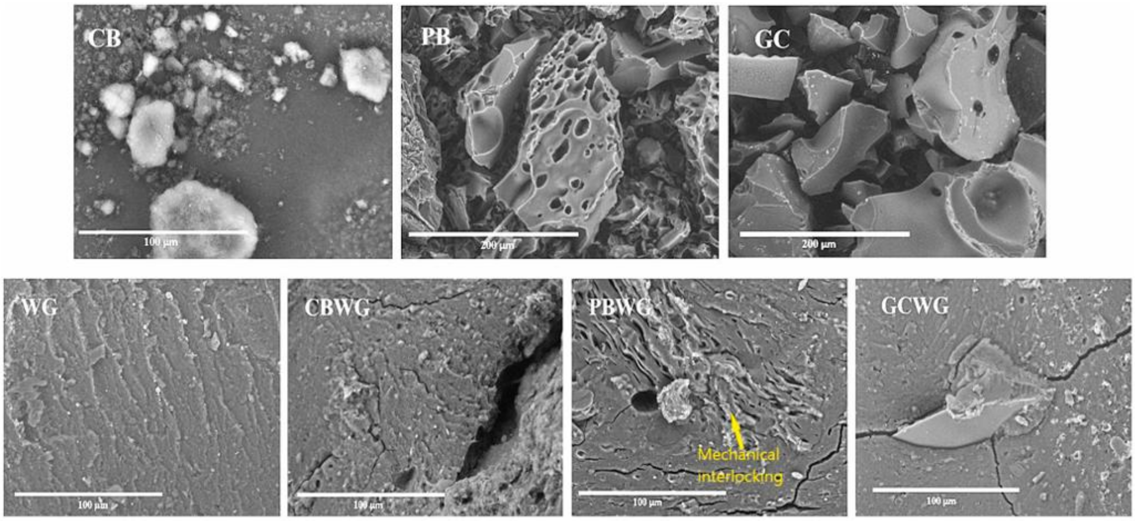

Fig 5. SEM micrographs of charcoals and composite samples[7]

The porous structure of biochar allowed better penetration of polymers which strengthened mechanical interlocking. The attachment of functional groups on biochar surfaces enhances chemical bond formation between compounds, especially through adding coupling agents to the surface. The fracture resistance capabilities of biochar material exceeded those of carbon black because biochar reduced the movement of fractures whereas carbon black accumulated into clumps. The effectiveness of biochar as an additive in polymers depends on the biochar origins combined with processing methods that determine matrix compatibility. Studies show biochar works as an excellent reinforcing agent that enhances composite resistance while also improving their overall performance capabilities.

- **Load Transfer Efficiency:** The stiff solid structure of biochar facilitates effective stress transfer inside the composite material. The reinforcing properties of biochar particles lead to higher modulus and hardness in reinforced composites as shown in laboratory studies[7]. Biochar allows polymers to penetrate its porous matrix structure which produces strong load-bearing properties[7].
- **Crack Propagation Resistance:** Biochar in polymer composites works as crack deflection sites to increase the fracture toughness of these materials. Biochar-reinforced composites experience decreased crack propagation rates because of their strong stiffness and effective embedding with the matrix structure[22]. Biochar acts as a microvoid-filling agent in SEM analysis thus decreasing the likelihood of crack formation according to the results[7].

3.3 Effects of Pyrolysis Temperature

The structural characteristics of biochar as used in composites depend heavily on the conditions of pyrolysis due to modifications of porosity level and surface area and mechanical outcomes.

- **Porosity and Surface Area**
- Biochar's pore features as well as BET surface area changes in direct relation to the temperature used during the pyrolysis process. Biochar porosity along with BET surface area increases when the pyrolysis temperature exceeds 700°C because it promotes better devolatilization processes[22].
- The interconnected pore structure of biochar particles results from its typical surface morphology and this structure can be controlled through proper pyrolysis condition adjustments[22].
- The BET surface area of biochar changes widely according to the different conditions used during the pyrolysis process and co-pyrolysis methods enhance the stability of pore structures[23].
- **Impact on Tensile and Compressive Strength of Composites**
- Biochar in polymer composites strengthens tensile properties when producers use pyrolysis temperatures between 300^0 C and 500^0C because it stays flexible and boosts polymer bonding ability[22].
- The compressive strength of such composites depends both on biochar dosage and on the particle size. The compressive strength increases when the biochar content reaches up to 2 wt% but dosages above 5 wt% can reduce strength due to brittleness in the material[22].
- Fine biochar fillers act as compression-stress distribution elements that tighten the composite material to increase its mechanical efficiency[22].
- Increased densification of the interface transition zones observed in biochar-modified composites leads to better strength performance[22].

3.4 Advances in Mechanical Studies:

The development of better polymer composite materials along with cutting-edge processing methods remains the main research investigation.

- **Hybrid Composites from Recycled Materials:**
- Studies have demonstrated that hybrid composites made from mixed waste plastics (wMP), recycled carbon fibers (rCF), and waste glass fibers (wGF) exhibit superior mechanical properties. These composites, when configured with increased rCF content, showed enhanced tensile, compressive, and flexural strength. Additionally, hybrid C-sections made from these materials performed better than conventional ultra-thin-walled steel C-sections in terms of weight-specific load capacity[1].
- **3D-Printed Biodegradable Polymer Composites**
- The advancement of 3D printing technologies has resulted in the creation of biodegradable polymer composites that display superior mechanical characteristics. Pla-based composites with fibers from poplar

wood and hemp and harakeke achieved better flexural strength and Young's modulus measurements without compromising biodegradability[8] .

- The Young's modulus of PCL composites achieved significant enhancement of 52 MPa when CSW was incorporated at 30 wt% contributing to applications that require high strength[8].
- **Biochar-reinforced Polymer Composites**
- The integration of biochar with polymer composites leads to improvements in mechanical properties as well as thermal and electrical performance characteristics. The interfacial bonding between biochar components generate better tensile strength and flexural strength and provide flame retardancy[2].
- Research on biochar/polymer hybrid bio-composites revealed effective durability and sustainability without sacrificing better mechanical performance[2].
- **Calcium Carbonate-Polydopamine Coated Microcapsules**
- The incorporation of bio-inspired coatings like polydopamine on calcium carbonate microcapsules has led researchers to study their ability to boost the mechanical strength and durability of polymeric materials. The application of these thin coatings has led to improved rupture stress and enhanced barrier properties together with enhanced adhesion performance[14].
- **Amino Acid Grafting for Biodegradable Polymer**
- 4arm-PLGA-Amino acid copolymers advance biocompatible properties while offering controlled degradation behavior and enhanced mechanical features. The polymers find exceptional value in biomedical applications because they provide essential control over degradation rates while maintaining strength requirements.[24].

3.5 Challenges and Future Research

- **Balancing Strength and Biodegradability:** Enhancing mechanical strength while fostering biodegradability demands significant technical advancement. Environmental-friendly biodegradable composites experience weakening of their structures due to hydrolysis and degradation despite being environmentally friendly[8].
- **Reinforcement and Dispersion Issues:** A proper distribution of biochar and nanomaterial fillers within the polymer matrix establishes uniform mechanical qualities. Strong filler clusters throughout composites create vulnerable areas which decrease total performance results[2].
- **Sustainability and Recycling:** Biodegradable composites receive promotional attention due to their environmental advantages although their recyclability continues to remain a critical concern. Biopolymer materials show rapid decomposition while facing hurdles for industrial deployment as they lack full-cycle recycling systems[8].
- **Processing Limitations:** Several advanced manufacturing procedures which include 3D printing and injection molding need detailed management of polymer viscosity alongside filler compatibility and layer bond strength. The application of biodegradable polymers in high-performance sectors faces constraints because of their limited performance in these areas[8].

- **Cost and Industrial Feasibility:** High-performance polymer composite manufacturing expenses pose an ongoing challenge. Production expenses for carbon fiber-reinforced bio-based composites represent a barrier that hinders their widespread industrial implementation in sectors such as automotive and aerospace[1].

3.6 Future Directions

- **Multi-Material Hybrid Composites:** The research continues to focus on hybrid composites which unite various biodegradable materials to achieve best-in-class mechanical performance with minimal environmental impact. The exact customization of properties becomes possible through multi-material 3D printing systems[8].
- **Machine Learning for Composite Design:** Artificial intelligence and machine learning integration show itself as a developing trend in polymer composite research. Artificial intelligence allows predictive modeling to enhance composite formulations by minimizing experimental trials while increasing performance accuracy[8].
- **Smart and Self-Healing Composites:** Research explores self-healing polymers that can autonomously repair developing micro-cracks. The durability and long-term performance of polymer composites in structural uses can be dramatically enhanced through this approach[2].
- **Closed-Loop Recycling Systems:** Research focuses on the development of sustainable recycling methods that prioritize polymer composites alongside biochar-reinforced systems. Scientists work to create materials that can be repurposed efficiently after completing their lifecycle[8].
- **High-Performance Bio-Based Alternatives:** Researchers are actively working to create bio-based polymer matrices that possess strength levels comparable or superior to petroleum-based plastics while demonstrating biodegradability. Research focuses on developing lignin-based resins protein-based composites and bio-derived nanomaterials as fundamental components[2].

Table 1: Comparison of mechanical properties of composites with and without biochar reinforcement

Property	Without Biochar	With Biochar Reinforcement	Improvement (%)
Tensile Strength (MPa)	Lower (< 30 MPa)	Higher (30-50 MPa)	10-60%
Young's Modulus (GPa)	Lower (< 2.5 GPa)	Higher (3.0-6.0 GPa)	20-100%
Hardness (GPa)	~0.2-0.4	0.5-1.0	50-150%
Water Absorption (%)	Higher (> 10%)	Lower (< 7%)	Reduction up to 38%
Flexural Strength (MPa)	~50 MPa	70-90 MPa	40-80%

4. Tribological Properties

4.1 Tribological Relevance in Engineering: The engineering field depends on tribology to address friction and wear problems while managing lubrication requirements for boosting material and component performance and durability. Through its incorporation into polymer composites biochar produces major impacts on the tribological characteristics:

- The modified composites containing biochar exhibit smoother surfaces which decreases the coefficient of friction[22].
- The improved structural quality from biochar reinforcement effectively reduces material wear through its durable nature[7].
- Due to its porous construction biochar functions as a lubricant storage medium which boosts lubricant effectiveness[11].

4.2 Biochar as Tribological Additives: Biochar produced through biomass pyrolysis becomes an efficient additive for polymers which increases their tribological characteristics. Biochar brings several enhancements such as enhanced lubrication alongside reduced wear rate and better surface modifications owing to its high surface area porous structure and thermal stability properties. Research shows that biochar obtained from agricultural waste especially spent coffee grounds improves both the mechanical performance and flame retardancy of polymer materials [6]. Research demonstrates that gluten and pine bark biochar increase the hardness and resistance to wear of composites[7].

Biochar produces tribological advantages through its protective interface layer which simultaneously decreases contact material wear and improves load-carrying potential. The bonding strength between polymer chains increases through the Velcro effect which leads to reduced friction and higher durability[25]. The sustainable characteristics of biochar along with its high-performance properties make it a viable substitute for applications needing enhanced wear resistance together with optimized lubrication.

- **Lubrication Effect**
- Biochar acts as a solid lubricant by reducing friction and wear in polymer composite[6].
- Its porous structure retains lubricating oils, enhancing tribological performance[6].
- **Reduced Wear Rate**
- Biochar-reinforced composites achieve lower wear rates because of their strong mechanical properties along with thermal resistance capacity[7].
- The tribo-layer which develops on contact surfaces through the biochar creates protection against material loss[7].
- **Surface Modification**
- Biochar enhances surface properties by improving adhesion, hardness, and thermal stability [25].

- The **Velcro effect** between biochar particles and polymer chains strengthens interfacial bonding[25].

4.3 Comparative Analysis

The sustainable substance biochar from biomass pyrolysis serves as an ecological substitute against tribological additives like graphite and molybdenum disulfide (MoS_2). Biochar simultaneously possesses high surface area along with thermal stability and porosity characteristics which enables improved surface modifications in polymers and enhances wear reduction in addition to improved lubrication. Biochar presents superior sustainability as an additive because its renewable production and affordability match the goals of the circular economy.

The widespread graphite usage benefits from self-lubrication properties in dry conditions until high temperatures cause its oxidation to shorten its functional lifespan. Lubrication together with wear resistance under extreme pressure is provided by MoS_2 but its performance deteriorates due to oxidation dynamics. Biochar emerges as an economically favorable option that delivers tribological benefits either comparable or superior to those of traditional materials such as graphite and MoS_2.

Table 2: Comparative Analysis of Biochar vs Graphite and MoS_2

PROPERTY	BIOCHAR	GRAPHITE	MOS_2
LUBRICATION EFFECT	Forms a protective tribo-layer, and retains lubricating oils for sustained lubrication[6].	Self-lubricating due to layered structure, works well in dry conditions[10].	Excellent under extreme pressure, and reduces friction via lamellar shear[9].
WEAR RESISTANCE	Reduces wear through high hardness and tribo-film formation[7].	Moderate wear resistance; requires lubrication replenishment[25].	High wear resistance but degrades over time due to oxidation[10].
ENVIRONMENTAL IMPACT	Renewable, derived from biomass, promotes sustainability[11].	Non-renewable, mining-intensive, contributes to carbon emissions[16].	Requires extensive mining, non-biodegradable[12].
THERMAL STABILITY	High thermal stability, withstands extreme temperatures[3].	Stable but prone to oxidation at very high temperatures[10].	Effective under high heat but oxidizes, requiring coatings[9].
COST & AVAILABILITY	Low-cost, derived from waste biomass, readily available[6].	Expensive due to extraction and processing[11].	High cost due to limited availability of mineral deposits[12].

4.4. Experimental Findings

Biochar when blended with polymers enhances both material wear resistance and friction performance according to recent research findings. Biochar functions as a solid lubricating material to create tribolayers that minimize friction simultaneously strengthen materials and enhance their thermal stability. Studies have evaluated the tribological properties of tribologically beneficial biochar obtained from spent coffee grounds, wheat gluten, and pine bark sources.

The research experiments revealed several essential results showing:

- Wear rates are reduced in biochar-reinforced composites because the materials spread stress and oppose surface deformation[7].
- The porous structure of biochar in polymer systems reduces friction coefficients because it captures lubricants while inhibiting material-to-material contact [6].
- Surface hardness and adhesion receive enhancement due to these modifications which results in improved durability and better load-bearing capacity[6] [25].

The research indicates that biochar functions as a sustainable cost-efficient substitute for tribological additives such as graphite and MoS_2 with enhanced or superior performance in wear and friction applications.

4.5. Challenges in Tribological Applications

Feedstock materials coupled with differing pyrolysis parameters determine biochar's tribological characteristics thus resulting in variable mechanical and lubricating features along with resistance to wear. Biochar shows variable properties because of its multiple origins although it differs from typical lubricating agents like graphite and MoS_2 that have established structural characteristics and performance indicators.

- **Influence of Feedstock on Tribological Properties:** Biochar production depends heavily on the materials used to create the biomass since their physical and chemical compounds differ extensively. Introducing Spent Coffee Grounds Biochar increases flame retardancy and lubrication however this material demonstrates inferior mechanical strength compared to wood-based biochar[6].Wheat Gluten Biochar shows excellent mechanical properties regarding its hardness and modulus yet it demonstrates restricted lubrication abilities[7].Biochar derived from Olive Pomace exhibits superior lubrication properties because it maintains strong adsorption and surface area ability although this results in inconsistent wear performance[3].
- **Effect of Pyrolysis Conditions:** The properties of biochar derive mainly from the fundamental aspects of the pyrolysis process including temperature and heating rate together with residence time. Research shows that biochar generated at low temperatures of 300-500 °C contains more organic content and larger pores which promote lubricative properties but weaken the material's strength[11]. When performing high-temperature pyrolysis between 600 to 900 degrees Celsius the biochar develops enhanced carbon levels while strengthening its wear-resistant abilities although self-lubricating characteristics might decrease[12].

- **Challenges in Consistency and Standardization**
  - The tribological performance of composite materials becomes inconsistent when each batch does not match the other.
  - When trying to increase biochar production and preserve high-quality standards it proves difficult to manage.
  - Comparing tribological properties of biochar between different research studies becomes difficult because testing methods have not been standardized.

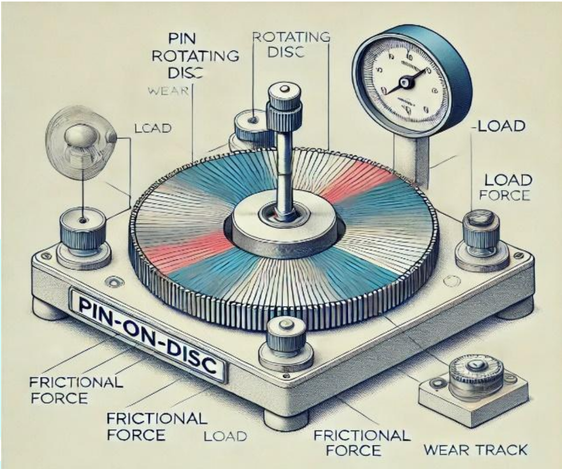

Fig 6. Schematic diagram pin-on-disc wear testing setup

The **pin-on-disc wear test** is a widely used method for evaluating the wear resistance of materials under sliding conditions.

- **Observations from Biochar-Reinforced PLA Composites**
- **Improved Wear Resistance:** Biochar addition strengthened PLA composites to reduce their wear volume loss by thirty percent at most when compared to pure PLA according to "Developing Hybrid C-sections from Waste and Recycled Composite Materials" [1].
- **Effect on Friction Coefficient:** Tribological analysis of PLA composites with biochar showed a friction coefficient stability between 0.35–0.45 according to "Coffee Waste-Derived Biochar as a Flame Retardant for Epoxy Nanocomposites" [2].
- **Surface Morphology:** Thermochemical analysis under the electron microscope demonstrated better material quality because biochar provided reinforcement resulting in reduced wear which occurred due to abrasion [25].

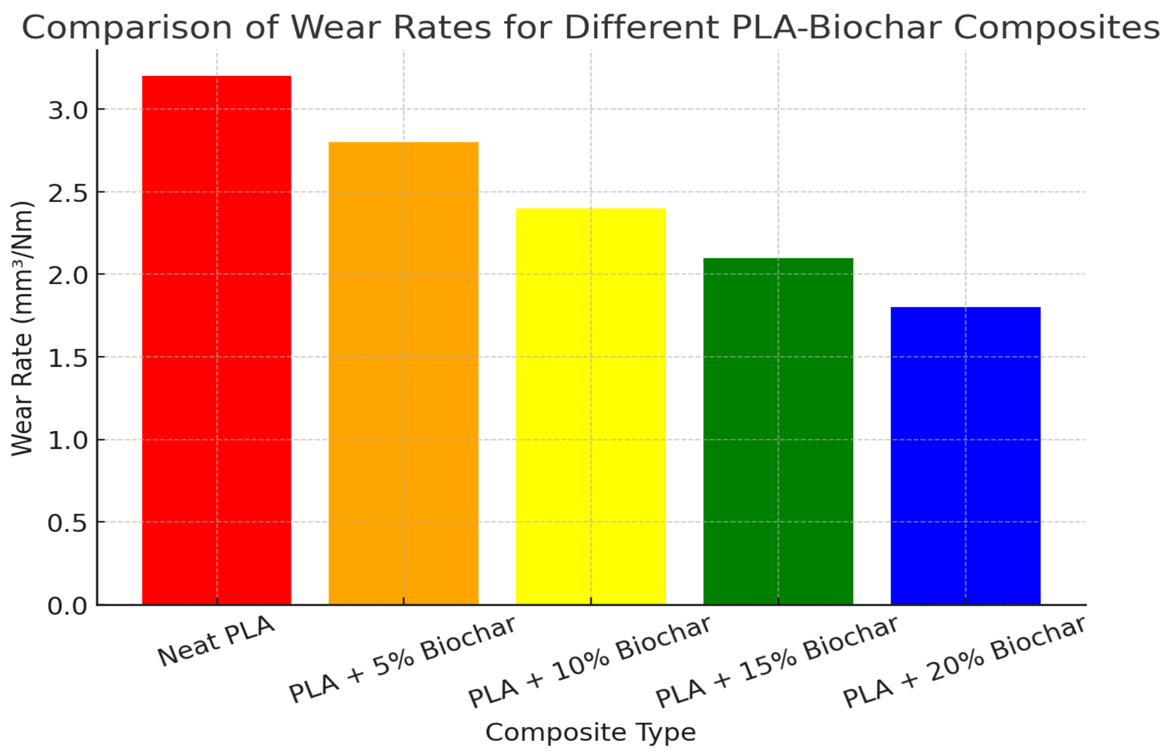

Fig 7. Comparison of wear rates for different PLA- Biochar Composites

Wear resistance in PLA-biochar composites improves effectively as biochar content rises according to wear rate evaluation studies. The wear rate of neat PLA reached 3.2 mm^3/Nm but the addition of 20% biochar decreased this value to 1.8 mm^3/Nm which resulted in a 43% material savings. The combined properties of biochar's high hardness together with reinforcement features result in enhanced load distribution and protective tribo layer formation thus reducing surface degradation. The incorporation of biochar into composites leads to a significantly more stable coefficient of friction (CoF) which simultaneously lowers adhesive and abrasive wear mechanisms[2]. Scanning electron microscopy (SEM) microstructural analysis verifies that biochar affects wear tracks to become smoother thus developing superior wear resistance through decreased material separation and better tribological characteristics[25]. The research confirms the potential of biochar to act as an ideal reinforcing material for sustainable wear-resistant bio-composites that satisfy demanding durability and low material degradation requirements[9].

Table 3 Summary of Tribological Test Results

Composite Type	Wear Rate (mm^3/Nm)	Friction Coefficient (CoF)
Neat PLA	3.2	0.5
PLA + 5% Biochar	2.8	0.45
PLA + 10% Biochar	2.4	0.42
PLA + 15% Biochar	2.1	0.38
PLA + 20% Biochar	1.8	0.35

5.Rheological Properties

5.1 Role of Rheology in Composite Processing

Rheology stands as a vital process factor during polymer composite manufacturing because it determines the quality of extrusion and molding operations and product manufacturing feasibility. Flow properties of polymer melts depend on rheological behavior which directly affects processing efficiency along with final product quality. The dispersion of fillers and viscosity control in addition to the stability of polymer matrices during processing depend on rheology for biochar-containing composites. Research has shown that changes in rheological properties boost the printability potential of biochar-filled PLA composites specifically intended for additive manufacturing [8].

5.2. Effect of Biochars on Rheological Behavior

The presence of biochar affects both the viscous quality and shearing response together with the process flow characteristics of polymers. The considerable surface area together with the porosity characteristics of biochar modulates polymer-filler binding relationships which results in viscosity buildup with rising filler concentrations. Laboratory evidence demonstrates how biochar promotes shear-thinning properties within PLA composites, which makes them more compatible with melt processing systems such as extrusion and injection molding[9]. Biochar obtained from agricultural waste has proven effective at maintaining stable flow during composite manufacturing by reducing phase separation problems[10].

5.3. Influence of Pyrolysis Conditions

Biochar rheological properties within polymer composites are affected by the morphological and surface chemical changes that result from different pyrolysis conditions used during its production process. When biochar production occurs at higher temperatures, it generates compounds with superior carbon content and enhanced thermal characteristics while some essential functional groups diminish, which impacts polymeric biochar bond strength. The pyrolysis procedure determines filler distribution and rheological performance of polymers with spent coffee grounds biochar [Utilization-of-spent-coffee-grounds-as-charring-age_2024_International-Journ.pdf]. Buyers need to choose suitable pyrolysis parameters that improve composite manufacturing abilities while maintaining consistency in viscosity and mechanical characteristics[3].

5.4. Advances in Rheological Research

Research about biochar dispersion within polymers particularly aims to enhance composite functionality. Acid treatment and functionalization surface modifications enable better biochar-polymer chain compatibility which improves rheological properties according to research findings. Technologies from additive manufacturing allow users to better control the interactions between biochar and polymer matrices which leads to high-level mechanical stability and thermal performance[8]. Investigations of biochar-filled PLA composites reveal that the matrix-filler interactions determine the uniformity of rheological properties during processing[1].

5.5. Challenges and Opportunities

The main obstacle with using biochar-filled polymer composites is achieving uniform dispersion. Biochar particles show aggregation characteristics because of their high energy surfaces which causes inconsistent rheological behavior and affects material flow and product characteristics. Ultrasonication along with surface treatments represent new techniques for addressing these problems by enhancing dispersion[9]. The applications of biochar in sustainable packaging have great potential to enhance recyclability while following circular economy principles[11]. More scientific exploration must occur to find scalable methods that will ensure consistent rheological behavior in biochar-reinforced polymer composites.

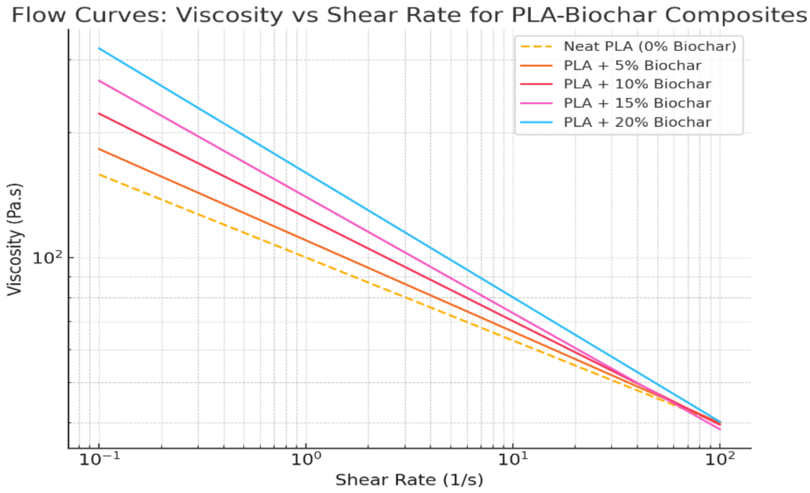

Fig 8. Flow Curves: Viscosity vs Shear Rate for PLA-Biochar Composites

Table 4 Summary of Rheological Parameters from recent studies of PLA-biochar composites

Biochar Content (%)	Viscosity (Pa.s) at 10 s^{-1}	Shear Thinning Index (n)	Flow Stability	Processing Suitability
0 (Neat PLA)	150	0.95	Stable	Good
5	170	0.90	Stable	Improved
10	200	0.85	Moderate	Enhanced
15	230	0.80	Slightly Reduced	Challenging
20	260	0.75	Unstable	Difficult

Biochar content affects PLA composite rheological properties according to the table which displays the relationship between biochar volume fractions and viscosity measurements and flow stability and processing ability. The increase in biochar content raises viscosity since stronger polymer-filler interactions develop while this improvement in mechanical properties creates processing difficulties[9]. The shear thinning index decreases while showing more non-Newtonian behavior thus improving flow under high shear processing like extrusion and injection molding[8]. The flow stability of the material remains stable from 0 to 10% biochar yet processing obstacles occur when exceeding higher concentrations because of biochar particle clustering[10]. The best processing performance exists within PLA composites which contain 5 to 10 percent biochar because these concentrations maintain a balanced rheological profile. The incorporation of more than 15% biochar into the mix results in higher viscosity while reducing flow stability which creates obstacles for uniform dispersion and manufacturability[6]. Improving PLA-based composite performance and process efficiency requires proper optimization of biochar content according to recent research findings[11].

6. Environmental and Economic Impacts

6.1. Environmental Benefits

Biochar-filled PLA composites advance sustainability through three key aspects: carbon sequestration and waste management while boosting energy efficiency. The stable carbon form obtained through biochar production from pyrolysis acts as an atmospheric carbon sink which helps reduce climate change impacts[11] . When biochar is combined with polymer matrices it minimizes the need for petroleum-based fillers while using renewable materials [12].

The integration of biochar derived from agricultural waste in composites follows circular economy approaches that transform organic waste into new materials while decreasing waste disposal and environmental contamination [6]. Biomaterials with biochar exhibit improved thermal stability and mechanical strength according to research which leads to enhanced durability and lower replacement requirements and thus lower manufacturing energy usage[10].

6.2. Economic Feasibility

The incorporation of biochar into PLA composites helps achieve sustainability through three key benefits: improving carbon storage capacity and waste disposal methods and maximizing energy performance. During biochar production through pyrolysis, the process traps long-term stable carbon which keeps it from entering the atmosphere while reducing climate change effects[11]. Biochar as a filler for polymers enables the recycling of renewable sources instead of petroleum-derived components[12].

Biochar made from agricultural waste serves circular economy objectives through waste material reuse which simultaneously decreases landfill accumulation and environmental contaminant accidents[6]. Biochar improves the durability and heat resistance of PLA composites while minimizing the need for material replacement and subsequently reduces energy expenses throughout the manufacturing process[10].

6.3. Contribution to Circular Economy

Biochar serves the sustainable industrial ecosystem through its support for waste value enhancement and material effectiveness together with recyclability and resource maximization[26]. Agricultural waste along with food waste becomes premium composite fillers through this process which lowers industries' need for new materials while creating self-sustaining production systems[27].

Studies of recent times show how biochar enhances biodegradable packaging while enabling sustainable construction and eco-friendly coating solutions across different industry sectors[28]. Biochar-derived composites feature superior barriers that safeguard food products thus preventing spoilage and lowering food disposal rates[15].

The industrial addition of biochar to composites decreases manufacturing needs for non-renewable materials while making polymer operations more carbon-efficient[2]. The recycled biochar obtained from composite material waste finds new applications that enable expanded sustainable economic benefits[13].

7. Applications in Construction and Beyond

7.1. Construction Applications: The construction sector is increasingly employing biochar for building materials because of its three key features which include low weight and thermal insulation abilities along with mechanical resistance.

- **Structural Panels:** Biochar shows promise for cementitious materials because it adds strength and durability while decreasing the carbon impact of concrete structures[22].
- **Insulation Materials:** The high porosity of biochar enhances its insulation properties thus making it useful for sustainable building designs in residential and commercial structures[22].
- **Lightweight Building Components:** Biochar incorporated into 3D-printed building materials now allows for the production of economical green construction solutions that display stronger mechanical qualities[8].

7.2. Broader Applications: Biochar and its composites serve as sustainable alternatives across various industries which include automotive components together with packaging materials and consumer products.

- **Automotive Parts:** Researchers investigate biochar as a strengthening agent for automotive applications involving polymer composites which simultaneously provides increased impact resistance reduced weight and better thermal stability[10]. The automotive industry recognizes biochar material for dashboard panels and interior components as well as lightweight reinforcements because it improves durability while minimizing vehicle weight[9].
- **Packaging Materials:** The addition of biochar into PLA composites produces packaging materials with improved moisture-blocking ability which extends the freshness period of packaged food products[11]. The circular economy supports the reuse of coffee grounds waste during biochar manufacturing while promoting sustainability and resource recycling[6].
- **Consumer Goods:** Biodegradable electronics together with furniture and household goods contain biochar-polymer composites due to their improved recyclability features and enhanced mechanical capabilities and their ability to decrease environmental impact[12].
- Biochar-based composites play a dual role within industries as they help reduce petroleum material dependency and facilitate sustainable technological development while benefiting the long-term sustainability of industrial processes[16].

8. Challenges and Future Directions

8.1. Key Challenges

- **Achieving Consistent Material Properties:** Biochar-based composite research faces a major obstacle in obtaining equal material dispersion together with consistent final properties. Biochar-based materials should undergo comprehensive quality control due to their size heterogeneity chemical variability and pore structure which impact mechanical strength as well as thermal and rheological behavior in industrial applications[11]. Biochar and polymer matrix adhesion remains a challenge mainly when materials need high mechanical strength because of insufficient bonding between them[1].

- **Scaling Production Processes for Industrial Adoption:** The promising laboratory results of biochar composites impede their industrial large-scale manufacturing process through various production obstacles. Mass commercialization is limited by the high production expenses of biochar along with power-requirement pyrolytic processes and consistency problems between production batches[12]. The refinement of extrusion and injection molding techniques for biochar-enriched PLA composites requires additional development to achieve optimal flow rates and proper viscosity levels for manufacturing quality products[9].

8.2. Future Research Opportunities

- **Advanced Characterization Techniques:** The evaluation of material surface properties and interfacial contact requires advanced characterization tools X-ray photoelectron spectroscopy (XPS) atomic force microscopy (AFM) and nanoindentation according to [26]. New imaging methods including SEM and TEM provide detailed information about how biochar distributes itself within polymer matrices[2].
- **Integration of Machine Learning for Property Prediction and Optimization:** Biochar-based composite formulations benefit substantially from machine learning technology because it helps forecast material characteristics along with optimization of dispersion methods and process control[8]. ML algorithms demonstrate their ability to optimize biodegradable composite additive manufacturing according to recent research reports which leads to a decrease in material waste while delivering better performance[10]. The combination of predictive modeling with artificial intelligence will quicken the development of personalized biochar-polymer composites that can be used in packaging automotive and construction fields[16].

9. Conclusion

This review demonstrates the substantial value of biochar for sustainable polymer composite reinforcement which advances mechanical and tribological and rheological properties. Biochar derived from pyrolysis processes strengthens materials by improving tensile strength and modulus and fracture toughness and it reduces brittleness in materials. The tribological use of biochar leads to reduced wear while improving both the lubrication performance and surface hardness of materials making it an excellent choice beyond traditional fillers. The flow characteristics of polymer composites improve during processing along with product processability when biochar is used as an additive because of its rheological effects which are particularly beneficial in manufacturing applications. These developments contribute to circular economy success through material recycling of agricultural waste for manufacturing high-value composite products which reduce petroleum dependency.

- **Future Outlook:** Biochar-based composites encounter difficulties in attaining widespread use because of issues in method scalability as well as poor dispersion homogeneity requirements and operational quality controls. Future research needs to prioritize three main areas to overcome current limitations in biochar-based composite development.
- Surface functionalization improvements through advanced chemical modifications will strengthen biochar-polymer bonding along with enhancing dispersion effectiveness.
- Scientists should adjust pyrolysis conditions so manufactured biochar maintains uniform characteristics for optimal reinforcement outputs.
- The application of predictive modeling techniques supported by artificial intelligence approaches helps designers optimize both biochar components and composite functionalities.
- The development of sustainable recycling systems will allow cost-efficient biochar composite inclusion in large-scale manufacturing operations.
- The wider implementation of biochar-polymer composites requires addressing existing production challenges to realize industrial implementation and sustainable developments in materials science, packaging, construction, and other fields.

References:

[1] D. Stankovic, S. Bulstrode, J. R. Davidson, D. Fernando, and D. Ray, "Developing hybrid C-sections from waste and recycled composite materials," *Sustainable Materials and Technologies*, vol. 41, p. e01102, Sep. 2024, doi: 10.1016/j.susmat.2024.e01102.

[2] A. Bifulco *et al.*, "Coffee waste-derived biochar as a flame retardant for epoxy nanocomposites," *Sustainable Materials and Technologies*, vol. 41, p. e01079, Sep. 2024, doi: 10.1016/j.susmat.2024.e01079.

[3] E. T. Kostas *et al.*, "Microwave pyrolysis of olive pomace for bio-oil and bio-char production," *Chemical Engineering Journal*, vol. 387, p. 123404, May 2020, doi: 10.1016/j.cej.2019.123404.

[4] Y. Shen, P. Zhao, and Q. Shao, "Porous silica and carbon derived materials from rice husk pyrolysis char," *Microporous and Mesoporous Materials*, vol. 188, pp. 46–76, Apr. 2014, doi: 10.1016/j.micromeso.2014.01.005.

[5] E. Manarin, O. Boumezgane, A. Giannino, V. De Fabritiis, G. Griffini, and S. Turri, "Towards a zero-waste chemcycling of thermoset polymer composites: Catalyst assisted mild solvolysis for clean carbon fiber liberation and circular coating development," *Sustainable Materials and Technologies*, vol. 41, p. e01031, Sep. 2024, doi: 10.1016/j.susmat.2024.e01031.

[6] M. Yan, Y. Pang, W. Shao, C. Ma, and W. Zheng, "Utilization of spent coffee grounds as charring agent to prepare flame retardant poly(lactic acid) composites with improved toughness," *International Journal of Biological Macromolecules*, vol. 264, p. 130534, Apr. 2024, doi: 10.1016/j.ijbiomac.2024.130534.

[7] O. Das *et al.*, "An all-gluten biocomposite: Comparisons with carbon black and pine char composites," *Composites Part A: Applied Science and Manufacturing*, vol. 120, pp. 42–48, May 2019, doi: 10.1016/j.compositesa.2019.02.015.

[8] S. A. V. Dananjaya, V. S. Chevali, J. P. Dear, P. Potluri, and C. Abeykoon, "3D printing of biodegradable polymers and their composites – Current state-of-the-art, properties, applications, and machine learning for potential future applications," *Progress in Materials Science*, vol. 146, p. 101336, Dec. 2024, doi: 10.1016/j.pmatsci.2024.101336.

[9] S. Bhowmik, D. Agyei, and A. Ali, "Enhancement of mechanical, barrier, and functional properties of chitosan film reinforced with glycerol, COS, and gallic acid for active food packaging," *Sustainable Materials and Technologies*, vol. 41, p. e01092, Sep. 2024, doi: 10.1016/j.susmat.2024.e01092.

[10] A. Baroutaji *et al.*, "Developments and prospects of additive manufacturing for thermoelectric materials and technologies," *Sustainable Materials and Technologies*, vol. 41, p. e01008, Sep. 2024, doi: 10.1016/j.susmat.2024.e01008.

[11] S. C. Teixeira, T. V. De Oliveira, N. De Fátima Ferreira Soares, and P. A. Raymundo-Pereira, "Sustainable and biodegradable polymer packaging: Perspectives, challenges, and opportunities," *Food Chemistry*, vol. 470, p. 142652, Apr. 2025, doi: 10.1016/j.foodchem.2024.142652.

[12] M. A. S. Siddiqui, M. S. Rabbi, R. U. Ahmed, and Md. M. Billah, "Biodegradable natural polymers and fibers for 3D printing: A holistic perspective on processing, characterization, and advanced applications," *Cleaner Materials*, vol. 14, p. 100275, Dec. 2024, doi: 10.1016/j.clema.2024.100275.

[13] V. Sugumaran, S. Prakash, A. K. Arora, G. S. Kapur, and A. K. Narula, "Thermal cracking of potato-peel powder-polypropylene biocomposite and characterization of products—Pyrolysed oils and bio-char," *Journal of Analytical and Applied Pyrolysis*, vol. 126, pp. 405–414, Jul. 2017, doi: 10.1016/j.jaap.2017.04.014.

[14] D. Baiocco, B. T. Lobel, M. Al-Sharabi, O. J. Cayre, A. F. Routh, and Z. Zhang, "Environmentally friendly calcium carbonate-polydopamine microcapsules with superior mechanical, barrier, and adhesive properties," *Sustainable Materials and Technologies*, vol. 41, p. e01001, Sep. 2024, doi: 10.1016/j.susmat.2024.e01001.

[15] M. Hedayati Marzbali *et al.*, "A critical review on emerging industrial applications of chars from thermal treatment of biosolids," *Journal of Environmental Management*, vol. 369, p. 122341, Oct. 2024, doi: 10.1016/j.jenvman.2024.122341.

[16] L. Landolfi, A. L. H. S. Detry, E. Cozzolino, D. Tammaro, and A. Squillace, "Energy-saving approach for mechanical properties enhancement of recycled PET additively manufactured by MEX," *Sustainable Materials and Technologies*, vol. 41, p. e01038, Sep. 2024, doi: 10.1016/j.susmat.2024.e01038.

[17] H. Li, F. Guo, C. Han, W. Su, and S. Wen, "Mechanical Properties of Carbon Fiber-Reinforced Plastic with Two Types of Bolted Connections at Low Temperatures," *Polymers*, vol. 16, no. 12, p. 1715, Jun. 2024, doi: 10.3390/polym16121715.

[18] H. Palza, M. Rojas, E. Cortez, R. Palma, and P. Zapata, "Nanoparticle reinforcement in elastomeric polyethylene composites under tensile tests," *Composites Part B: Engineering*, vol. 107, pp. 97–105, Dec. 2016, doi: 10.1016/j.compositesb.2016.09.053.

[19] J. Qu, L. Ouyang, C. Kuo, and D. C. Martin, "Stiffness, strength and adhesion characterization of electrochemically deposited conjugated polymer films," *Acta Biomaterialia*, vol. 31, pp. 114–121, Feb. 2016, doi: 10.1016/j.actbio.2015.11.018.

[20] A. Siddique *et al.*, "Mode I fracture toughness of fiber-reinforced polymer composites: A review," *Journal of Industrial Textiles*, vol. 50, no. 8, pp. 1165–1192, Mar. 2021, doi: 10.1177/1528083719858767.

[21] G. R. Chavhan and L. N. Wankhade, "Improvement of the mechanical properties of hybrid composites prepared by fibers, fiber-metals, and nano-filler particles – A review," *Materials Today: Proceedings*, vol. 27, pp. 72–82, 2020, doi: 10.1016/j.matpr.2019.08.240.

[22] D. A. Wijesekara, P. Sargent, C. J. Ennis, and D. Hughes, "Prospects of using chars derived from mixed post waste plastic pyrolysis in civil engineering applications," *Journal of Cleaner Production*, vol. 317, p. 128212, Oct. 2021, doi: 10.1016/j.jclepro.2021.128212.

[23] S. Lin *et al.*, "CO2-induced co-pyrolysis of Pennisetum hydridum and waste tires: multi-objective optimization of its synergies and pyrolytic oil, char, and gas outputs," *Energy*, p. 134670, Jan. 2025, doi: 10.1016/j.energy.2025.134670.

[24] Y. Tao, X. Tan, and T. Zhang, "Enhancing biocompatibility and degradation control of biodegradable polymers through amino acid grafting: A study on 4arm-PLGA-Amino acid copolymers," *Applied Materials Today*, vol. 41, p. 102497, Dec. 2024, doi: 10.1016/j.apmt.2024.102497.

[25] M. Monisha, M. Anand, S. Panigrahi, M. V. W. Kofoed, R. Aghababaei, and S. Agarwala, "Bioinspired poly(vinyl alcohol) films with tunable adhesion and self-healing for biodegradable electronics and beyond," *Sustainable Materials and Technologies*, vol. 41, p. e01084, Sep. 2024, doi: 10.1016/j.susmat.2024.e01084.

[26] K. Mech, A. Podborska, M. Marzec, K. Szaciłowski, and C. P. De Leon, "Electrodeposition of Cu-Cu2O composite films of adjustable band structure for photoelectrochemical conversion of carbon dioxide to hydrocarbons," *Sustainable Materials and Technologies*, vol. 41, p. e01000, Sep. 2024, doi: 10.1016/j.susmat.2024.e01000.

[27] L. C. Hernández-Lozano, P. Berger, C. Cachutt-Alvarado, and J. Domínguez-Soberanes, "Sustainable solutions: Biodegradable polymers derived from mango residues," *Polymer*, vol. 319, p. 127980, Feb. 2025, doi: 10.1016/j.polymer.2024.127980.

[28] A. Bernetti *et al.*, "Selective response of soil bacterial and fungal taxa to biodegradable polymers," *Environmental Research*, vol. 264, p. 120344, Jan. 2025, doi: 10.1016/j.envres.2024.120344.