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Development of High-Performance Composite Materials from Recycled Footwear Using Nano and Chemical Reinforcement Techniques

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Abstract:

This study focuses on the sustainable recycling of discarded footwear waste into high-performance polymer composites through advanced chemical and nano-reinforcement techniques. The process involves shredding footwear waste and blending it with polymeric matrices consisting of approximately 60 wt% recycled footwear base material, 25 wt% polyurethane (PU), and 10 wt% styrene-butadiene rubber (SBR) to enhance flexibility and strength. To further improve mechanical performance, 5wt% nano-fillers comprising 3 wt% silica nanoparticles and 2 wt% carbon nanotubes (CNTs) are introduced, optimizing wear resistance and tensile strength. Interfacial bonding between the recycled matrix and polymer additives is enhanced using 2–3 wt% silane coupling agents and 1 wt% maleic anhydride-grafted polymer modifiers, resulting in improved load transfer and composite stability.The developed composites are processed using automated sorting, nano-enhanced material treatment, and smart extrusion-based manufacturing, yielding uniform, durable, and aesthetically customizable materials. The resulting products demonstrate superior mechanical integrity, making them suitable for footwear components, resilient flooring, and decorative elements. This innovative system embodies circular economy principles, minimizing waste, conserving resources, and contributing to eco-friendly material innovation within the footwear industry.

***Keywords* — Footwear waste recycling ,Sustainable composites ,Polymer reinforcement,Styrene-butadiene rubber (SBR),Polyurethane (PU),Silica nanoparticles,Carbon nanotubes,Chemical modification,Circular economy**

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I. Introduction

The global footwear industry produces millions of tons of waste annually, much of which ends up in landfills due to the complex combination of materials such as rubber, polyurethane (PU), leather, and plastics. These materials are non-biodegradable, leading to long-term environmental pollution and resource wastage. Conventional disposal methods like incineration not only release toxic gases but also fail to recover valuable polymers that could be reused. Therefore, there is a pressing need for a sustainable and efficient recycling process that converts footwear waste into new, high-performance materials.

This study focuses on developing eco-friendly composite materials from recycled footwear waste by integrating polymer reinforcement, nano-fillers, and chemical modification techniques. The proposed system utilizes approximately 60 wt% shredded footwear waste, blended with 25 wt% polyurethane (PU) and 10 wt% styrene-butadiene rubber (SBR) to improve flexibility, toughness, and elasticity. To further enhance the structural integrity and mechanical strength, 5 wt% nano-fillers (including 3 wt% silica nanoparticles and 2 wt% carbon nanotubes) are incorporated. Chemical compatibilizers such as 2–3 wt% silane coupling agents and 1 wt% maleic anhydride-grafted polymers are added to improve interfacial bonding between the recycled base and polymeric phases.

The integration of automated sorting, nano-enhanced material processing, and smart manufacturing technologies enables efficient recycling and uniform dispersion of nano-additives. This approach not only enhances mechanical, thermal, and wear resistance properties but also allows for customized coloration and design flexibility in the final composite products.By implementing circular economy principles, the proposed recycling system reduces environmental impact, promotes material recovery, and supports sustainable production within the footwear sector. Ultimately, this research demonstrates how waste footwear can be transformed into value-added, high-performance composite materials suitable for various applications such as footwear components, resilient flooring, and decorative structures, contributing to resource conservation and sustainable material innovation.

II. Research Gap

Despite increasing interest in sustainable materials, significant gaps remain in the recycling of footwear waste. Most existing studies focus on mechanical recycling of rubber or leather scraps into low-value products such as mats, fillers, or insulation, with limited research on converting footwear waste into high-performance polymer composites with enhanced mechanical and thermal properties. Furthermore, while polymer blending is common, few studies have explored the integration of nano-fillers, such as silica nanoparticles and carbon nanotubes, along with polymer modifiers, to improve interfacial bonding, wear resistance, and overall mechanical performance of recycled composites. Current processing methods are often manual or semi-automated, resulting in non-uniform material properties, and advanced techniques like nano-enhanced treatment and smart extrusion remain underexplored. Additionally, most research lacks a thorough assessment of environmental benefits, including waste reduction, resource conservation, and circular economy contributions. Finally, the application scope of recycled footwear materials is largely limited to low-end products, with minimal investigation into functional composites suitable for industrial uses such as footwear components, resilient flooring, or decorative elements. This study addresses these gaps by combining chemical modification, nano-reinforcement, and automated processing to produce durable, high-performance composites from discarded footwear, advancing both material innovation and sustainable waste management.

III. Problem Statement

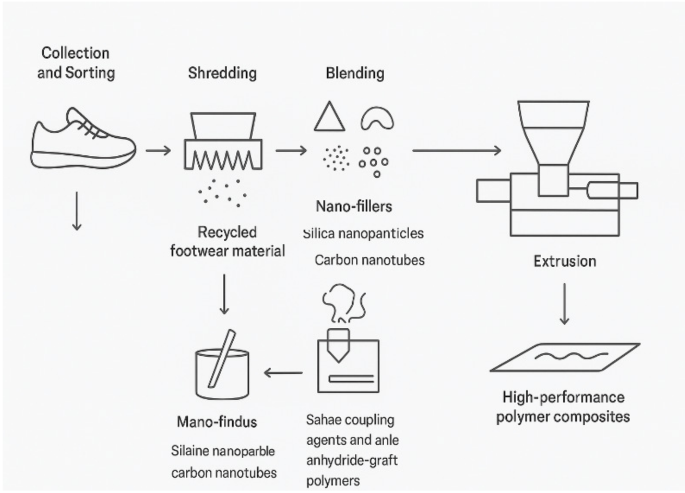
The global footwear industry generates a significant amount of post-consumer waste, including worn-out shoes, scraps, and rejected products. Most of this waste is disposed of in landfills or incinerated, leading to environmental pollution, resource depletion, and greenhouse gas emissions. Traditional recycling methods focus on low-value applications, such as mats or fillers, and fail to utilize the full potential of footwear waste.

Moreover, existing recycling techniques rarely incorporate advanced chemical modifications, polymer blending, or nano-reinforcements, resulting in materials with inadequate mechanical strength, durability, and wear resistance for industrial applications. The lack of standardized, automated processing methods further limits uniformity and scalability. Consequently, there is an urgent need for a sustainable and efficient approach to convert footwear waste into high-performance, value-added composites that meet functional requirements while promoting circular economy principles and reducing environmental impact.

IV. Objectives

1. To develop a sustainable method for recycling discarded footwear waste into high-performance polymer composites.
2. To optimize the composition of recycled footwear, polyurethane (PU), styrene-butadiene rubber (SBR), and nano-fillers (silica nanoparticles and carbon nanotubes) for enhanced mechanical strength, flexibility, and wear resistance.
3. To improve interfacial bonding between recycled footwear material and polymer additives using chemical modifiers such as silane coupling agents and maleic anhydride-grafted polymers.
4. To design and implement an automated processing system incorporating nano-enhanced treatment and smart extrusion for uniform and durable composite production.
5. To evaluate the mechanical, thermal, and aesthetic properties of the developed composites for potential applications in footwear components, resilient flooring, and decorative elements.
6. To contribute to circular economy practices by reducing footwear waste and promoting sustainable material innovation.

V. Design



VI. Working

The project focuses on converting discarded footwear waste into high-performance polymer composites through a systematic recycling and fabrication process. Initially, post-consumer footwear is collected and sorted to remove contaminants such as metal parts, fabric, and adhesives. The clean footwear waste is then shredded into small granules to serve as the base material for the composite.

The shredded material is blended with a polymeric matrix consisting of polyurethane (PU) and styrene-butadiene rubber (SBR) in predefined ratios to enhance flexibility and mechanical strength. Nano-fillers, including silica nanoparticles and carbon nanotubes (CNTs), are incorporated to improve tensile strength, wear resistance, and overall durability. Chemical modifiers such as silane coupling agents and maleic anhydride-grafted polymers are added to strengthen interfacial bonding between the recycled matrix and polymer additives, ensuring effective load transfer.

The mixture undergoes nano-enhanced treatment and is processed using a smart extrusion system to produce uniform, dense, and aesthetically customizable composite sheets. The final composites are tested for mechanical properties such as tensile strength, elasticity, and wear resistance, as well as thermal stability. The developed materials can then be used for industrial applications like footwear components, resilient flooring, and decorative products, demonstrating a sustainable approach to circular material reuse.

VII. Advantages

1. Reduces footwear waste and supports recycling.
2. Enhanced strength, flexibility, and wear resistance.
3. Suitable for footwear, flooring, and decorative items.
4. Better thermal stability and abrasion resistance.
5. Customizable: Can be shaped, colored, or textured.
6. Uses waste materials, reducing raw material costs.
7. Compatible with automated manufacturing.

VIII. Application

1. Footwear parts: Soles, insoles, and uppers.
2. Eco-friendly flooring: Durable and resilient floors.
3. Decorative items: Panels, trims, and design features.
4. Industrial components: Lightweight, wear-resistant parts.
5. Construction materials: Protective panels and coverings.

IX. Future Scope

The future scope of recycled footwear polymer composites is highly promising, with potential expansion into various industrial sectors such as automotive, packaging, and consumer goods, where lightweight, durable, and eco-friendly materials are in demand. Advancements in nanotechnology could introduce novel or hybrid nanofillers, further improving mechanical strength, thermal stability, and functional properties such as antimicrobial performance. There is also potential for developing smart composites with self-healing, conductive, or sensing capabilities for advanced applications. Scaling up recycling processes for other polymer or mixed plastic wastes can further reduce environmental impact, supporting circular economy principles. Additionally, these composites can be adapted for 3D printing and customized manufacturing, enabling the creation of complex, aesthetically appealing, and high-performance products.

X. Conclusion

The study demonstrates that discarded footwear waste can be effectively transformed into high-performance polymer composites through chemical modification and nano-reinforcement techniques. Incorporating recycled footwear material with PU, SBR, and nano-fillers such as silica nanoparticles and carbon nanotubes significantly enhances mechanical strength, flexibility, and wear resistance. The use of coupling agents and polymer modifiers ensures strong interfacial bonding, resulting in stable and durable composites. These materials are suitable for diverse applications, including footwear components, resilient flooring, decorative elements, and industrial parts, while promoting sustainability and reducing environmental impact. Overall, this innovative approach supports circular economy principles, offering an eco-friendly and cost-effective solution for recycling footwear waste into valuable, high-performance materials.

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XII. Reference

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