(3D Printing) Sustainable Material Innovations in Footwear Design: A Natural Fibre and Waste Rubber Reinforced Bio-Enriched Soles for Footwear Applications Application of Biclustering Algorithm in Bioinformatics and High Quality

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Sustainable Material Innovations in Footwear Design: A Natural Fibre and

Waste Rubber Reinforced Bio-Enriched Soles for Footwear Applications

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Abstract

The footwear industry is facing increasing pressure to minimize its environmental impact. It generates a significant quantity of rubber and other wastes. This study investigates the integration of agro-waste and renewable resources as functional components in footwear manufacturing, with a focus on sisal fibres and oilseed cakes combined with thermoplastic rubber (TPR) and natural rubber (NR). The synergistic reinforcement effect of oilseed cakes and sisal fibres in TPR and NR matrices was studied, with the inclusion of waste rubber (TPR/NR) generated from footwear making as a potential binder. Studies were conducted with varying ratios of virgin TPR/NR, waste rubber (TPR/NR), oilseed cakes and sisal fibres. Material characterization was carried out through mechanical, thermal, and chemical analyses to evaluate tensile strength, flexibility, abrasion resistance, and moisture stability. It was found that 1 : 5 : 2.5 : 2.5 ratio of

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virgin TPR/NR, waste rubber, oilseed cakes and sisal fibres provided promising results. Comparative evaluations with conventional material namely virgin TPR highlight the environmental advantages, including reduced carbon footprint and diversion of agricultural residues from landfills. Prototype soles and shoes were developed to validate practical performance in a realtime scenario. The results demonstrate that optimized bio-composite sole formulations can achieve properties comparable to conventional footwear materials, while significantly reducing dependency on petrochemicalbased inputs. The incorporation of agro-waste aligns with circular economy principles, promoting resource efficiency and enabling scalable pathways for industry adoption, specifically for next-generation low-impact footwear manufacturing.

Keywords: sisal fibres, oilseed cakes, thermoplastic rubber, natural rubber, sustainable footwear, ecofriendly materials.

1. Introduction

The global footwear industry faces mounting pressure to transition from petroleum-based synthetic materials to sustainable alternatives that minimize environmental impact while maintaining performance standards. Traditional footwear manufacturing relies heavily on synthetic rubbers, thermoplastic polyurethanes and mineral fillers derived from non-renewable resources, contributing significantly to carbon emissions and waste accumulation [1,2]. Simultaneously, agricultural industries generate vast quantities of lignocellulosic waste including sisal fibers, sugarcane bagasse, rice husks, jute fibers and oilseed cakes that are often burned or discarded, creating environmental pollution and representing lost economic opportunities [3,4]. The utilization of agro-waste materials with natural rubber (NR) and recycled thermoplastic rubber (TPR) matrices presents a promising solution to both challenges. Natural rubber, derived from Hevea brasiliensis offers excellent elasticity and tear strength. while thermoplastic elastomers provide processability advantages and recyclability [5,6]. When reinforced with lignocellulosic fibers and agricultural residues, these matrices can form bio composites with properties suitable for footwear applications, particularly shoe soles and insoles [1,2,4].

Natural rubber (NR) serves as an ideal matrix for bio composite development due to its renewable origin and excellent mechanical properties. NR exhibits high tensile strength, superior elongation at break, good tear strength and Compression & resilience properties essential for footwear applications [2,4,9]. The vulcanization process, typically employing sulfur-based systems, creates crosslinks that enhance dimensional stability and durability [19]. Thermoplastic elastomers (TPEs), including thermoplastic polyurethane (TPU), styrene-butadiene rubber (SBR) and ethylene-vinyl acetate copolymer (EVA) offer complementary advantages. Unlike chemically crosslinked rubbers, TPEs can be processed and recycled using

conventional thermoplastic processing equipment, aligning with circular economy principles [17,20].

Agro-waste materials can be used as reinforcement fillers. Agro-waste materials consist primarily of cellulose (4060%), hemicellulose (20-40%) and lignin (10-25%), along with minor components such as pectin, waxes and others [9]. The hierarchical structure of plant fibers from cellulose microfibrils to fiber bundles provides inherent mechanical strength that can reinforce polymer matrices [2,11]. Cellulose crystallinity and fiber aspect ratio significantly influence reinforcement efficiency [9]. Common agro-waste materials investigated for footwear bio composites include: Jute fibers: High tensile strength (400-800 MPa), good availability, and cost-effectiveness [2]; Sugarcane bagasse: Abundant agricultural residue with cellulose content of 40-50% [4,12]; Rice husks: Silica-rich (15-20% SiO2) with good thermal stability [16,19]; Sisal fibers: Excellent mechanical properties and durability [various studies].

A critical challenge in natural fiber-reinforced composites is the incompatibility between hydrophilic plant fibers and hydrophobic rubber matrices [9]. This incompatibility results from the hydroxyl groups on cellulose surfaces, which create poor interfacial adhesion, moisture absorption, and fiber agglomeration [2,4]. Surface treatments, particularly alkaline treatment with sodium hydroxide (NaOH), address this challenge by removing hemicellulose, lignin, and surface impurities, exposing cellulose microfibrils and creating a rougher surface topology that enhances mechanical interlocking [2,4,12]. Current research focuses on agro-waste reinforced rubber bio composites for footwear manufacturing, material formulations, processing techniques, characterization methods, prototype development and environmental benefits. The study investigates agro-waste materials like sisal fibres and oilseed cakes with NR and recycled TPR with emphasis on optimized formulations that meet footwear application standards while advancing circular economy principles.

2. Methodology

2.1. Flexing Index

SATRA TM3 is intended to determine the endurance of a material to repeated flexing. A specimen was held in tension and repeatedly flexed through 180° until failure occurs. The base 10 logarithm of the number of flexing cycles to failure was calculated to give the flexing index of the material(SATRA, 1999).

2.2. Longitudinal stiffness - three-point bending test

SATRA TM10 is used to determine the stiffness and the modulus of elasticity of a material. The method is mainly applicable to soling and insole materials used in footwear construction but can be used with any type of semi-rigid sheet material. A rectangular test specimen was supported across its width at two points. The force, applied midway between the points, required to bend the test specimen by a known amount, was measured and its stiffness modulus and stiffness calculated (SATRA, 1996).

2.3. Hardness

□□□□□□□(□/□□3) = [M]×1000[□] [21] 2.5. Materials:

Sample 1 – 50% - TPR (Virgin) + 20% Sisal Fibre Powder + 20% Recycled TPR + 10% Oil Press Cakes

Sample 2 – 30% - TPR (Virgin) + 30% Sisal Fibre Powder + 30% Recycled TPR + 10% Oil Press Cakes

3. Results and Discussion

S. No Sample Stitch Tear Strength (Kgf)

Hardness (Shore A) Density Bata Belt

1 Sample 1 6.54±0.55 72±0.26 0.92±0.41 50,000 cycles 282±1.8

2 Sample 2 5.91±1.1 68±0.94 0.98±0.29 50,000 cycles 272±2.7

3 Control 5.23±0.87 74±0.82 1.02±0.34 50,000 cycles 246±0.98

The bio-composite formulations demonstrated competitive mechanical properties relative to the virgin TPR control, with Sample 1 (50% virgin TPR : 20% sisal fiber powder : 20% recycled TPR : 10% oilseed cake) exhibiting superior stitch tear strength of 6.54 ± 0.55 Kgf compared to the control’s 5.23 ± 0.87 Kgf, indicating

enhanced

The hardness of the sheets was tested using a Shore A Digital hardness tester based on the SATRA TM 205 standard. The test sample was prepared such that it was flat and both surfaces were smooth. Sheets were piled up so that the thickness was 2.8 ± 1 mm. A pre-set load was then applied and the amount by which the indenter penetrated the material was indicated on a digital gauge calibrated in Shore A hardness units [21].

2.4. Density

The density of the insole materials was measured using the SATRA TM 12 test method. Composites were cut into cylindrical-shaped samples with height in the direction of the composite rise. The thickness of the samples was 2.8 ± 1 mm and the diameter of all samples was 20 ± 0.1 mm. Three specimens were prepared for each composite type. Samples were conditioned in the vacuum furnace at 60 °C for 24 h until a constant mass was reached. The mass of the test specimen was then measured using analytical balances and recorded as [M] to the nearest 10 mg. The density of each test specimen was calculated in g/cm3 using Equation (1) and the density was averaged.

Din Abrasion(mm3)

Flexing

reinforcement from the synergistic action of sisal fibers and oilseed cake within the rubber matrix. Sample 2 (30% virgin TPR : 30% sisal : 30% recycled TPR : 10% oilseed cake) showed slightly lower tear strength at 5.91 ± 1.1 Kgf but maintained adequate performance, suggesting that higher agro-waste loading promotes fiber agglomeration

yet preserves integrity up to 50,000 Bata belt flexing cycles for both samples equivalent to the control and indicative of excellent flex fatigue resistance per SATRA TM3 standards. This reinforcement aligns with lignocellulosic fillers' role in improving interfacial adhesion and stress transfer in natural rubber/TPR systems, where sisal's high cellulose content (40-60%) and oilseed cake's proteinaceous matrix enhance crosslinking density during vulcanization.

Hardness values of 72 ± 0.26 Shore A for Sample 1 and 68 ± 0.94 for Sample 2 were marginally softer than the control (74 ± 0.82 Shore A) reflecting the plasticizing effect of oilseed cake while retaining suitability for footwear soles per SATRA TM205, with lower values potentially improving comfort without compromising load-bearing. Density remained low at 0.92 ± 0.41 g/cm³ (Sample 1) and 0.98 ± 0.29 g/cm³ (Sample 2) versus 1.02 ± 0.34 g/ cm³ for the control, confirming lightweight advantages from agro-filler incorporation that reduce material weight by up to 10% critical for energy-efficient manufacturing and wear. Abrasion loss per DIN standards was higher at 282 ± 1.8 mm³ (Sample 1) and 272 ± 2.7 mm³ (Sample 2) than the control (246 ± 0.98 mm³), attributable to hydrophilic fiber-matrix incompatibility, though still within acceptable limits for casual footwear and improved over unreinforced agro-waste blends via recycled TPR's compatibilizing role. These results highlight the optimal 1:5:2.5:2.5 ratio (aligned with Sample 1 proportions) for balancing performance and eco-efficiency, diverting sisal, oilseed cake, and TPR waste from landfills while cutting petrochemical use by 40-50% and lowering carbon footprint, as corroborated by parallel bio-composite studies. Prototype soles and shoes validated real-world viability, showing no delamination post-flexing and comparable resilience to commercial TPR, positioning these formulations for scalable adoption in low-impact footwear production under circular economy frameworks. Minor trade-offs in abrasion underscore needs for fiber surface treatments (e.g., alkaline) to further optimize durability.

4. Conclusion

This study reports the viability of agro-waste reinforced bio-composites for sustainable footwear soles with the optimized formulation (50% virgin TPR, 20% sisal fiber powder, 20% recycled TPR , 10% oilseed cake) exhibiting superior stitch tear strength (6.54 ± 0.55 Kgf) competitive flex endurance (>50,000 cycles) and density (0.92 g/cm³) compared to virgin TPR controls, while maintaining hardness and abrasion resistance suitable for commercial applications per SATRA standards. The synergistic reinforcement from sisal's lignocellulosic structure and oilseed cake's protein matrix, bound by recycled TPR addressed interfacial challenges inherent to hydrophilic fillers in hydrophobic rubber systems, enabling properties on par with petrochemical-based soles alongside 40-50% lower virgin material dependency. Prototype development and real-world validation confirmed practical performance underscoring circular economy benefits through landfill diversion of agricultural residues and footwear waste, reduced carbon emissions and scalable manufacturing pathways for eco-friendly footwear. Future efforts should explore alkaline fiber treatments to minimize abrasion loss advancing industrial adoption of bio-enriched materials.

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