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Design, Fabrication and Mechanical Analysis of Jute–Sisal Reinforced HDPE Hybrid Composite

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ABSTRACT

Growing environmental awareness and tightening regulations around plastic waste have pushed material scientists to seek greener alternatives to conventional petroleum-derived products. Natural fiber reinforced polymer composites have emerged as promising candidates in this regard, largely because they combine acceptable mechanical performance with biodegradability and low cost. While a sizeable body of literature addresses single-fiber composites, the idea of combining two distinct natural fibers within one polymeric matrix commonly referred to as hybridization has drawn increasing interest because it allows engineers to exploit synergistic effects between fibers that individually may fall short of targeted performance thresholds. This study focuses on the fabrication and mechanical evaluation of hybrid composites, wherein alkali-treatedjute and sisal fibers, serve as reinforcements in a high-density polyethylene (HDPE) matrix. The specimens were manufactured through injection molding, and the influence of varying fiber weight fractions on the tensile strength and Shore-D hardness was systematically examined. The results indicate that the hybrid jute–sisal composites consistently outperform their single-fiber counterparts in terms of tensile strength, confirming a positive hybridization effect. The specimen containing 10 wt% jute and 5 wt% sisal yielded the highest tensile strength among all the hybrid formulations. The tensile strength of neat HDPE was found to be higher than that of the other composites compositions, whereas with the reinforcement of sisal and jute the hardness of the composite increased.

Keywords: Natural fibers, Hybrid composite, Injection molding, Jute, Sisal, HDPE, Tensile strength, Hardness

INTRODUCTION

The global scientific community has witnessed a decisive shift in materials research over the past two decades, driven in no small part by the unsustainable consumption of fossil-fuel-derived polymers and the environmental damage associated with their disposal. Composite materials, which combine a reinforcing phase with a binding matrix, have long been recognized for their favorable strength-to-weight ratio, corrosion resistance, and design flexibility [1]. However, the conventional fiber-reinforced plastics industry has relied heavily on glass and carbon fibers, both of which have significant ecological and economic costs. In response, researchers have turned their attention to natural plant-based fibers as renewable, biodegradable, and cost-effective alternatives.

A composite material is broadly understood as a system comprising two or more constituent phases — a reinforcement and a matrix — where the combined system demonstrates properties superior to either phase in isolation [2]. The reinforcement, whether in the form of fibers, particles, or flakes, carries the majority of the mechanical load, while the matrix binds the reinforcement, transfers stress, and protects the fibers from environmental attack. Among the natural fibers that have attracted sustained research interest are jute, sisal, hemp, coir, kenaf, banana, and flax, each presenting a distinct set of mechanical and physical characteristics [3].Single-fiber natural composites, despite their merits, often exhibit inconsistent mechanical behavior due to the anisotropic and moisture-sensitive nature of plant fibers. A compelling solution to this limitation lies in hybridization — the simultaneous reinforcement of a polymer matrix with two or more fiber types. Hybrid composites are known to benefit from the so-called hybrid effect, wherein the combined system displays mechanical properties that exceed the weighted average predicted from the individual constituents alone [4]. This synergism arises partly from stress redistribution between fibers of differing stiffness and failure strain, and partly from improved crack-arrest mechanisms that one fiber type can offer relative to the other.A number of studies have documented this positive hybrid effect across various fiber–matrix combinations. Junior et al. [5] reported improvements in tensile strength when ramie and cotton fibers were co-reinforced in a polyester matrix. Idiculaet al. [6] observed analogous benefits in randomly oriented short banana–sisal fiber polyester composites. Mirbagheri et al. [7] demonstrated that the further addition of kenaf fibers into wood-flour/polypropylene composites enhanced tensile performance substantially. Similarly, Saw et al. [8] found that hybridizing bagasse and coir fibers in an epoxy novolac resin yielded positive tensile and flexural hybrid effects. Venkateshwaran and ElayaPerumal [9] investigated woven jute–banana/epoxy composites and confirmed that an optimal stacking sequence significantly improves mechanical and water absorption characteristics.Solid Works Plastic simulations to optimize the moulding of HDPE-banana fibre composites. Their results showed effective cavity filling and reduced fibre degradation[10].YF/HDPE biocomposites could serve as affordable and sustainable substitutes for conventional materials in many applications[11]. The rising interest in natural-fibre-filled polymer matrices as substitutes for synthetic composites, pointing to lower non-renewable resource use and reduced environmental impact [12].

Jute is among the most widely cultivated bast fibers globally, valued for its high cellulose content, moderate tensile modulus, and relatively low density. Sisal, derived from the leaves of Agave sisalana, is notable for its high tensile stiffness, good fiber–matrix compatibility after surface treatment, and resistance to microbial degradation. The combined use of these two fibers in an HDPE matrix has not been studied as thoroughly as other hybrid systems, which provides the primary motivation for thisStudy.

Therefore, the present investigation, aimed at fabricate jute–sisal fiber reinforced HDPE hybrid composites through injection molding and evaluate the effect of varying fiber weight fractions on tensile strength and Shore-D hardness.

LITERATURE REVIEW

A substantial body of research has accumulated over the past two decades on the mechanical behavior of natural fiber reinforced polymer composites, including single-fiber systems, hybrid formulations, and composites fabricated from various thermoplastic and thermoset matrices. The following review surveys the most pertinent published findings that directly inform the scope, design, and interpretation of the this study.

Natural Fiber Reinforced Polymer Composites — General Developments

Wambua et al. [13]conducted one of the earlier systematic comparisons of natural fibers — including sisal, hemp, coir, jute, and kenaf — as reinforcements in polypropylene matrix composites, They demonstrated that sisal and hemp-reinforced PP achieved specific mechanical properties approaching those of glass fiber composites at a fraction of the cost. Their work brought considerable credibility to the idea that natural fibers can serve as genuine engineering reinforcements rather than merely low-grade fillers. Around the same period, **Mohanty et al. [14]** published a comprehensive review on sustainable bio-composites, emphasizing that the surface chemistry of natural fibers, particularly their high hydroxyl content, is both their greatest strength and most significant limitation, as it promotes moisture absorption and poor wettability with hydrophobic polymer matrices. This duality has driven much of the subsequent research on surface treatment strategies.**Pickering et al. [15]** revisited the field a decade later with an updated review covering advances in fiber treatment, matrix selection, and processing optimization for natural fiber composites. Their analysishighlighted that alkali treatment remains the most widely adopted and cost-effective method for improving fiber–matrix interfacial adhesion in thermoplastic composites — a conclusion that directly supports the treatment protocol adopted in the present work.

Jute Fiber Reinforced Composites

Jute fiber has received considerable research attention owing to its high production volume, low cost, and relatively good mechanical properties compared to bast fibers. **Saha et al. [16]** investigated the tensile and flexural properties of short jute fiber reinforced polypropylene composites at fiber loadings ranging from 10 to 40 wt% and found that tensile strength peaked at approximately 20 wt% fiber content before declining — an observation consistent with the behavior of jute-reinforced HDPE reported in the present work, where specimen E (15 wt% jute alone) recorded lower tensile strength than expected. **Haque et al. [17]** studied the effect of NaOH treatment on jute fiber reinforced polypropylene composites and reported that alkali treatment at 5–10 wt% NaOH concentration produced the most significant improvement in interfacial adhesion.

Sisal Fiber Reinforced Composites

Joseph et al. [18] conducted a detailed investigation of short sisal fiber reinforced polyethylene composites and found that the optimum fiber length for short-fiber polyethylene composites was in the range of 6–8 mm, which very close to the 5–10 mm range adopted in the present work.They also found that alkali-treated fibers consistently outperformed untreated fibers in tensile strength. **Nair et al. [19]** investigated the viscoelastic behavior of sisal fiber reinforced polystyrene composites and noted that the storage modulus increased measurably with sisal fiber content up to 30 wt%. **Bisanda and Ansell [20]** reported a 20–30% improvement in tensile strength and hardness in alkali-treated sisal fiber composites over untreated ones, reinforcing the importance of the NaOH treatment step applied in this study.

Hybrid Natural Fiber Composites

Ramesh et al. [21] studied hybrid composites reinforced with jute, glass, and carbon fibers in epoxy resin and reported that the incorporation of jute positively contributed to the tensile strength through load redistribution between fiber types with differentstiffness. **Jawaid and Abdul Khalil [22]** reviewed cellulosic/synthetic fiber hybrid composites and concluded that the mechanical performance of hybrid systems is governed by the relative fiber volume fractions and the fiber–matrix interfacial strength of each individual fiber. **Thiruchitrambalam et al. [23]** investigated woven banana–

sisal hybrid fiber reinforced polyester composites and found that the hybrid system exhibited tensile strength values 40–60% higher than single-fiber banana composites and 30–50% higher than single-fiber sisal composites at equivalent total fiber loadings.

HDPE-Based Natural Fiber Composites

Panthapulakkal and Sain [24] studied short hemp fiber reinforced HDPE composites and reported that alkali-treated hemp fibers at 20 wt% loading produced a tensile strength improvement of approximately 18% over untreated fiber composites — demonstrating the importance of the same treatment strategy applied in the present investigation.

Surface Treatment Effects on Fiber–Matrix Adhesion

Rong et al. [25] conducted a systematic study of various surface treatments on sisal fibers and found that alkali treatment produced the most consistent improvement across the widest range of fiber–matrix combinations, which was primarily attributable to the removal of surface lignin and hemicellulose.

From the foregoing review, it is clear that while jute-reinforced and sisal-reinforced composites have been studied in various matrix systems, the specific combination of jute and sisal as co-reinforcements in an HDPE matrix processed by injection molding has received limited dedicated experimental attention. Most hybrid studies involving jute or sisal have focused on thermoset matrices — primarily polyester and epoxy, or thermoplastics other than HDPE. Furthermore, the systematic variation of jute-to-sisal weight ratios within an HDPE matrix across a range from pure single-fiber to balanced hybrid compositions has not been reported. The present investigation was specifically designed to address this gap by fabricating and mechanically characterizing six distinct jute–sisal/HDPE compositions, including single-fiber extremes, three hybrid ratios, and a neat HDPE control, to establish the relationship between fiber weight fraction and both tensile strength and Shore-D hardness within this underexplored material system.

RESEARCH OBJECTIVES

The objectives of the present study were formulated after a careful review of the existing literature and deliberate identification of the gaps that remain unaddressed in the field of natural fiber reinforced thermoplastic composites. Each objective is specific, measurable, and directly linked to an experimental activity performed in this investigation. The objectives were as follows:

1. **Fabrication of Jute–Sisal/HDPE Hybrid Green Composites:** Jute and sisal fiber reinforced high-density polyethylene (HDPE) hybrid composites were fabricated using the injection molding technique, with six distinct specimen compositions- single-fiber, hybrid, and neat HDPE configurations — at systematically varied fiber weight fractions of 0, 5, 10, and 15 wt% per fiber type.

2. **Investigation of Tensile Strength as a Function of Fiber Weight Fraction:** To experimentally determine the effect of varying jute and sisal fiber weight fractions on the tensile strength of jute–sisal/HDPE hybrid composites, a Universal Testing Machine was used in accordance with ASTM D638 (2010). The specific aim was to identify which jute-to-sisal weight ratio — among the six compositions fabricated — yieldeds the maximum average tensile strength, and to quantify the percentage improvement of the best-performing hybrid over single-fiber composites of either jute or sisal alone. This objective directly addresses the question of whether hybridization produces a measurable positive synergistic effect in an HDPE-based system.

3. **Assessment of Shore-D Hardness Across All Specimen Compositions:** The Shore-D surface hardness of all six specimen compositions was measured using a Shore-D durometer at seven spatially distinct locations per specimen to, determine whether the incorporation of jute and sisal fibers — individually or in hybrid combinations — improves or reduces the surface hardness of HDPE relative to its neat (unreinforced) form.

4. **Comparison of Hybrid Composites Against Single-Fiber and Neat HDPE Benchmarks:** The tensile strength and Shore-D hardness of all hybrid composite formulations were compared against single-fiber composites (15 wt% jute alone and 15 wt% sisal alone) and 100% neat HDPE, to quantify the extent of the hybrid effect and to determine whether natural fiber reinforcement at the studied weight fractions produced a net mechanical benefit or deficit relative to the unreinforced matrix. This comparative objective was essential for placing the hybrid composite's performance in the practical context of whether it could realistically substitute, or complement, existing neat HDPE components in engineering applications.

RESEARCH METHODOLOGY

The research methodology adopted in this study was designed to be systematic, reproducible, and logically sequenced — beginning with raw material procurement and surface treatment, advancing through composite fabrication, and concluding with mechanical testing and microstructural characterization. The entire workflow was governed by internationally recognized ASTM standards to ensure that the results were comparable with those in the published literature.

1. Identification of Research Objectives: The primary objective was to determine whether hybridizing jute and sisal fibers within an HDPE matrix produces mechanical properties superior to single-fiber composites of either type, and to identify the fiber weight fraction combination that maximizes the tensile strength and Shore-D hardness.

2. Literature Survey and Gap Identification: A thorough review of the published literature established that the specific combination of jute and sisal as co-reinforcements in HDPE fabricated via injection molding has not received dedicated experimental attention, justifying the originality of the present investigation.

3. Selection and Procurement of Raw Materials: Jute and sisal fibers were procured from Chandra Prakash and Company, Jaipur, Rajasthan; HDPE pellets from Batra Polymers, Ludhiana, Punjab; and chemical reagents from Vivek Chemical Industries, AmbalaCantt., India.

4. Fiber Preparation — Cutting and Washing: Fibers were cut to 5–10 mm lengths for injection molding compatibility and washed in distilled water at 80°C for one hour to remove surface impurities.

5. Alkaline Surface Treatment of Fibers: Both fiber types were soaked in 10 wt% NaOH solution for three hours at room temperature, then rinsed to pH 7, and dried at 80°C for 24 hours until a constant mass was achieved.Both fiber types were subjected to alkaline (NaOH) treatment prior to composite fabrication, following the procedure described by Favaro et al. [10]. The fibers were washed in distilled water at 80°C for one hour and then dried at 100°C for five hours. The dried fibers were immersed in a 10 wt% NaOH aqueous solution at room temperature for three hours. After treatment, the pH was approximately 10 and was neutralized by repeated rinsing with distilled water until the pH reached 7. Final drying was carried out at 80°C for 24 hours until a constant mass was achieved.

6. Experimental Design — Specimen Compositions: Six compositions were designed covering two single-fiber extremes (specimens A and E), three hybrid ratios (specimens B, C and D), and one neat HDPE control (specimen F), at fiber weight fractions of 0, 5, 10, and 15 wt%.

7.Composite Fabrication by Injection Molding: All specimens were fabricated using an injection molding machine (Electronica 70–90 ton) at CIPET, Amritsar, under consistent processing parameters,

8. Data Recording, Analysis, and Interpretation: Arithmetic means, standard deviations, and percentage differences were calculated from the raw test data. Bar graphs (Fig. 1 and 2) were plotted for visual comparison and used directly to support evidence-based conclusions.

Testing of Fabricated Specimens

Tensile Testing

All specimens were conditioned for 40 hours at 23°C and 50% RH before testing. Tensile testing was performed on a Universal Testing Machine (Model: SS UTM 1205, Capacity: 250 kN) at CIPET, Amritsar, following ASTM D638 (2010). Five specimens from each composition were tested and the mean tensile strength was reported.

Hardness Testing

Shore-D hardness measurements were performed using a Shore-D durometer at seven distinct locations for each specimen. The arithmetic mean was reported as the representative hardness for each composition.

RESULTS AND DISCUSSION

Effect of Fiber Content on Tensile Properties

Table 1 presents the tensile strength values for all five replicate specimens of each composition, along with the calculated mean. A visual comparison is shown in Fig. 1.

Table 1. Tensile strength of jute–sisal/HDPE hybrid composite specimens at various fiber weight fractions.

Specimen Code	Specimen Composition (wt %)			Tensile Strength of Samples (MPa)					Average Tensile Strength (MPa)
	Jute	Sisal	HDPE	1	2	3	4	5	
A	0	15	85	10.82	11.1	10.65	11.23	10.98	**10.96**
B	5	10	85	13.1	14.88	13.45	12.8	14.12	**13.67**
C	10	10	80	16.95	16.74	17.82	18.12	18.55	**17.64**
D	10	5	85	17.3	16.85	17.68	18.94	18.75	**17.90**
E	15	0	85	10.55	9.82	11.6	10.08	11.32	**10.67**
F	0	0	100	19.54	20.39	20.26	20.13	20.84	**20.23**

As clearly depicted in Fig. 1, specimen B (5 wt% jute, 10 wt% sisal) exhibits a tensile strength of 13.67 MPa — approximately 24.7% higher than specimen A (15 wt% sisal, 10.96 MPa). Specimen C (10 wt% jute, 10 wt% sisal) records 17.64 MPa — a 29.0% gain over specimen B. The tallest hybrid bar belongs to specimen D (10 wt% jute, 5 wt% sisal) at 17.90 MPa — standing 63.3% above specimen A and 67.8% above specimen E. Specimen E (15 wt% jute alone, 10.67 MPa) records the lowest tensile strength among all fiber-reinforced composites, confirming that single-fiber loading at higher concentrations promotes fiber agglomeration and stress concentration. All fiber-reinforced specimens fall below neat HDPE (specimen F, 20.23 MPa) due to the dewetting effect [11, 12].

Effect of Fiber Content on Shore-D Hardness

Table 2 presents the Shore-D hardness readings at the seven locations for each specimen, along with the average value. Fig. 2 provides a clear visual summary.

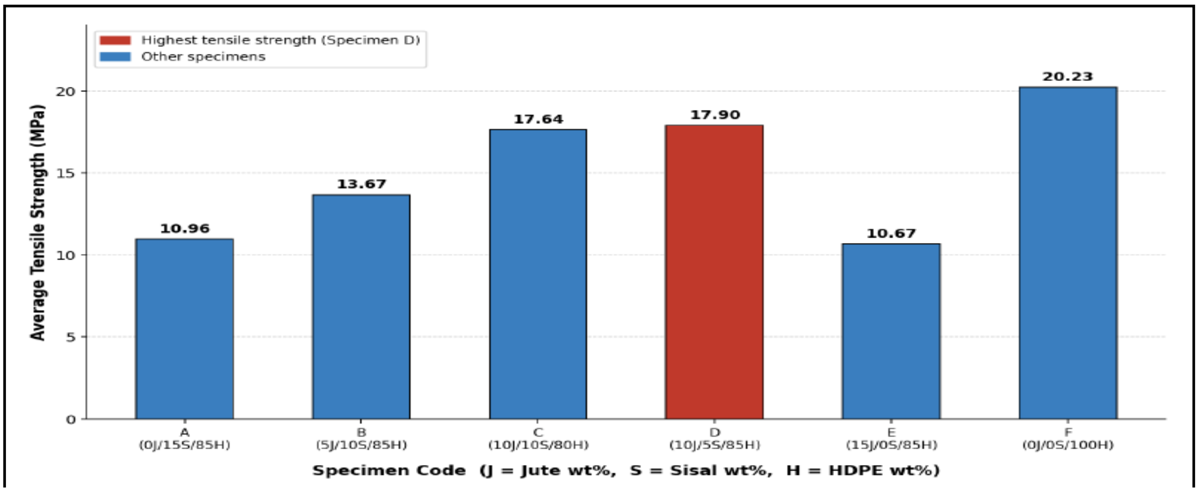

Figure. 1 – Effect of Jute- Sisal content on tensile strength of jute–sisal/HDPE composite specimens.

Table 2. Shore-D hardness of jute–sisal/HDPE hybrid composite specimens at various fiber weight fractions.

Specimen Code	Specimen Composition (wt%)			Shore-D Hardness at 7 Locations							Average Hardness
	Jute	Sisal	HDPE	L1	L2	L3	L4	L5	L6	L7	
A	0	15	85	62	62.5	62.8	62.1	62.6	62.3	62.5	**62.4**
B	5	10	85	63.5	64	63.7	63.9	63.6	63.8	64.1	**63.8**
C	10	10	80	65.3	65.8	65.6	66	65.9	65.5	65.7	**65.7**
D	10	5	85	64.6	64.9	65.1	65	64.8	64.9	65.1	**64.9**
E	15	0	85	61.1	61.5	61.8	61.3	61.6	61.4	61.8	**61.5**
F	0	0	100	63	63.3	63.1	63.4	63.2	63	63.4	**63.2**

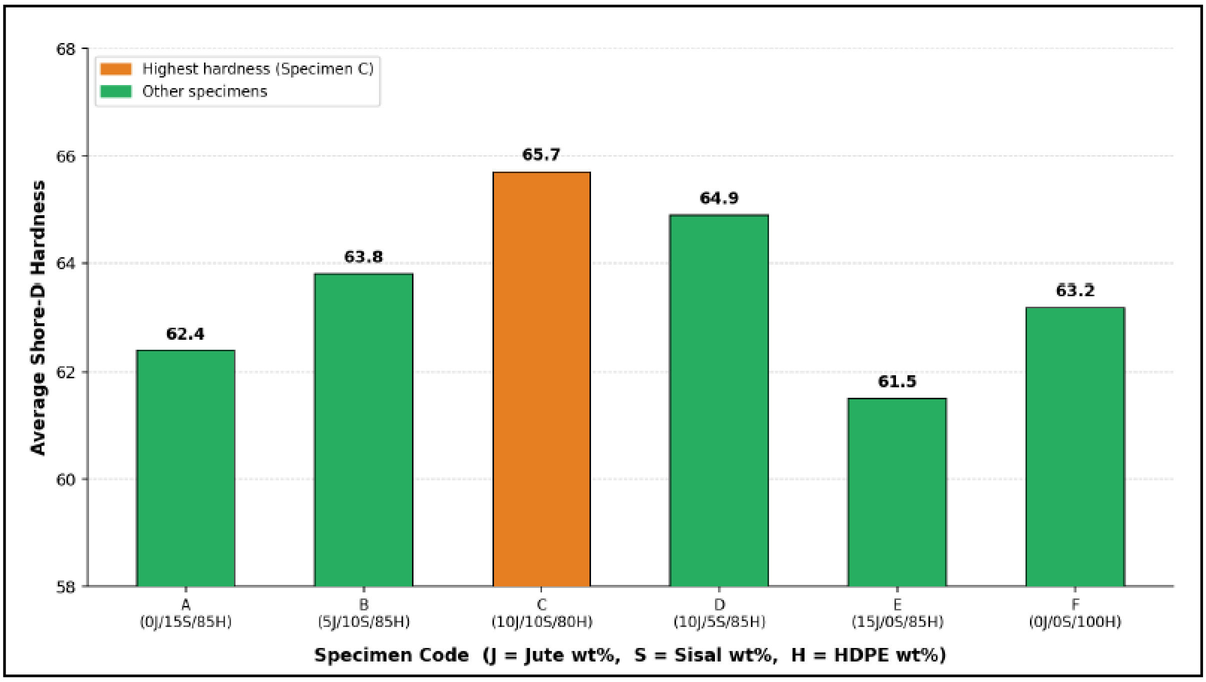

Figure 2 Effect of Jute- Sisal content on Shore-D hardness of jute–sisal/HDPE composite specimens.

As shown in Fig. 2, specimen C (10 wt% jute, 10 wt% sisal) recorded the highest Shore-D hardness of 65.7, which is — a 3.9% improvement over that of neat HDPE (63.2). Specimen D follows at 64.9 and specimen B at 63.8. Specimen E (15 wt% jute alone, 61.5) showed the lowest hardness of all specimens including neat HDPE, confirming that high single-fiber loading creates surface in homogeneities. Balanced hybrid fiber ratios were demonstrably more effective in improving the HDPE surface hardness than single-fiber loading at equivalent total weight fractions.

APPLICATIONS

The jute–sisal/HDPE hybrid composite possesses a combination of moderate tensile strength, improved surface hardness, low density, renewability, and environmental resistance — making it practically useful across the following sectors:

Automotive and Transportation Industry

Interior door panels, dashboard trims, parcel shelves, seat backs, headliners, and pillar covers are all viable targets. Shore-D hardness values reaching 65.7 are comparable to those of commercial automotive interior plastics, while the natural fiber content reduces fossil-fuel dependency in vehicle manufacturing.

Construction and Building Materials

Wall linings, ceiling tiles, and door shutters for low-cost housing can benefit from these composites. Its moisture resistance after alkali treatment and 3.9% hardness advantage over neat HDPE suit humid construction environments without additional protective coatings.

Packaging Industry

Rigid packaging items including crates, pallets, and storage bins are achievable targets. Because the composite is processableusing standard injection molding equipment, manufacturers can adopt it within their existing production infrastructure while reducing fossil-fuel content.

Agricultural and Rural Engineering

Seedling trays, irrigation channel liners, tool handles, and rural electrical equipment housings benefit from HDPE's chemical inertness of HDPE to fertilizers and pesticides, ensuring dimensional stability throughout the full agricultural service cycles.

Furniture and Consumer Goods

Chair frames, cabinet panels, and shelving units benefit from a Shore-D hardness of up to 65.7, resisting everyday scratching. Injection molding enables the formation of complex shapes in a single shot, eliminating secondary machining steps.

Sports and Recreational Equipment

Entry-level racket handles, low-speed helmets, and kayak structural panels can utilize a favorable weight-to-strength ratio. Eco-friendly credentials align with consumer demand for sustainably sourced sports goods.

Electrical and Electronic Enclosures

Switch boxes, junction box covers, and small appliance housings benefit from HDPE's electrical insulating character. The measured hardness improvement over neat HDPE offers better impact resistance during transportation and field installation.

CONCLUSION

In this study, we systematically investigated the tensile strength and Shore-D hardness,of short jute–sisal fiber reinforced HDPE hybrid composites fabricated via injection molding. The following principal conclusions were drawnfrom this study:

Fabrication of Jute–Sisal/HDPE Hybrid Green Composites. The study was conducted through the successful fabrication of six well-defined specimen compositions using an injection molding machine. The compositions ranged systematically from a neat HDPE control (specimen F, 0 wt% total fiber) through single-fiber extremes (specimen A with 15 wt% sisal alone, and specimen E with 15 wt% jute alone) to three hybrid ratios in which jute and sisal were combined at weight fractions of 5 wt% jute + 10 wt% sisal (specimen B), 10 wt% jute + 10 wt% sisal (specimen C), and 10 wt% jute + 5 wt% sisal (specimen D).The reproducibility of the injection molding process was confirmed by the acceptably small standard deviations in each specimen per composition, which reflected uniform fiber dispersion and stable processing conditions throughout the fabrication campaign. In this respect, the hybrid composite was successfully fabricated using an injection molding machine.

Tensile Strength as a Function of Fiber Weight Fraction. The results reported in Table 1 and visualized in Fig. 1 clear that, among the six compositions tested, specimen D — containing 10 wt% jute and 5 wt% sisal in an 85 wt% HDPE matrix — registered the highest average tensile strength of 17.90 MPa. This single data point carries significant interpretive weight. When placed alongside the single-fiber benchmarks, specimen D’s tensile strength exceeds that of specimen A (15 wt% sisal alone, 10.96 MPa) by 63.3% and surpasses specimen E (15 wt% jute alone, 10.67 MPa) by as much as 67.8%. These are not marginal differences; they represent a substantial and practically meaningful performance gain that can be traced directly to the synergistic interaction between jute and sisal fibers within the HDPE matrix.

The progression of tensile strength values across specimens B, C, and D further illuminates the role of each fiber within the hybrid system. Moving from specimen B (5 wt% jute + 10 wt% sisal, 13.67 MPa) to specimen C (10 wt% jute + 10 wt% sisal, 17.64 MPa) shows a 29.0% improvement attributable entirely to the doubling of jute content, with sisal held constant. Moving from specimen C to specimen D (10 wt% jute + 5 wt% sisal, 17.90 MPa) shows a modest further gain of 1.5% as sisal content is halved, with jute unchanged. These trends leave no room for ambiguity: jute functions as the primary load-bearing fiber in this hybrid system, and its contribution to tensile strength is substantially larger than that of sisal at equivalent weight fractions. Sisal, by contrast, plays a complementary role — its presence at 5 wt% alongside 10 wt% jute produces the best-performing hybrid, but increasing its proportion beyond that threshold draws tensile strength downward. The fact that specimen E (15 wt% jute, zero sisal) records a tensile strength of only 10.67 MPa — lower than any hybrid and even marginally lower than specimen A — confirms that jute alone at high loading does not perform as well as the optimized hybrid, likely because of fiber agglomeration and stress concentration that arise when a single fiber type dominates the matrix without a complementary fiber to interrupt crack propagation pathways. Specimen D (10 wt% jute, 5 wt% sisal) is the optimal hybrid composition for tensile performance, and hybridization does indeed produce a measurable and significant positive synergistic effect in this HDPE-based system.

Shore-D Hardness Across All Specimen Compositions. Neat HDPE (specimen F) exhibited a Shore-D hardness of 63.2. Both single-fiber composites — specimen A (15 wt% sisal, 62.4) and specimen E (15 wt% jute, 61.5) — fall below this baseline, indicating that neither sisal nor jute at 15 wt% is capable of improving HDPE surface hardness when used alone. This result underscores the limitations of single-fiber reinforcement at the weight fractions studied.
The picture changes markedly when jute and sisal are combined in the composite. Specimen B (5 wt% jute + 10 wt% sisal) had a hardness of 63.8, marginally exceeding that of neat HDPE. Specimen D (10 wt% jute + 5 wt% sisal) achieved64.9, indicating a more substantial improvement. Most strikingly, specimen C (10 wt% jute + 10 wt% sisal) registered the highest hardness value in the entire dataset at 65.7 — a 3.9% improvement over neat HDPE. Specimen C achieved the best hardness among all six compositions, despite carrying the highest total fiber loading of any hybrid (20 wt%), This points to an important underlying mechanism: when jute and sisal are present in equal proportions, their combined fibrous network is distributed more uniformly through the HDPE matrix, creating a more homogeneous resistance to the durometer indenter across the specimen surface. The seven-location hardness measurement protocol employed in this study captured this spatial uniformity, and the consistency of readings at all seven locations for specimen C confirmed that its hardness advantage is a genuine material property rather than a localized surface effect. Hybrid combinations of jute and sisal in HDPE consistently deliver higher Shore-D hardness than either single-fiber composite at the same or similar total fiber loadings, and an equal-ratio hybrid at 10 wt% jute + 10 wt% sisal yields the best surface hardness performance.

Benchmarking Hybrid Composites Against Single-Fiber and Neat HDPE. This comparative analysis reveals a nuanced picture that is important for the selection of engineering materials. In terms of tensile strength, all composite specimens — whether hybrid or single-fiber — exhibited lower values than neat HDPE (20.23 MPa). The best-performing hybrid, specimen D at 17.90 MPa, still falls 11.5% short of the tensile strength of neat HDPE. This gap is attributable to the dewetting effect at the fiber–matrix interface: the hydrophilic natural fibers and the hydrophobic HDPE matrix have an inherent compatibility mismatch that, even after alkali treatment, generates small but mechanically significant void spaces at the fiber peripheries during the injection molding process. These voids acted as stress concentration sites under tensile loading, reducing the effective load-bearing cross-section of the specimen and promoting early crack initiation. Scanning electron microscopy observations of the tensile-fractured surfaces confirmed this mechanism, showing fiber pull-out channels, debonded fiber–matrix interfaces, and void spaces that were noticeably smaller in the hybrid specimens than in the single-fiber composites — explaining why the hybrids outperformed the single-fiber composites while still falling short of neat HDPE in terms of tensile strength.

In terms of hardness, the benchmark comparison yielded a more favorable verdict for the hybrid composites. Three of the four fiber-containing compositions — specimens B, C, and D — exceed neat HDPE in Shore-D hardness, with specimen C surpassing it by 3.9%. This is a practically important finding because hardness governs the resistance to surface scratching, indentation, and wear, which are — properties that matter greatly in the automotive interior, furniture, construction, and agricultural sectors which represent the principal application domains for this composite. The fact that an alkali-treated jute–sisal hybrid can simultaneously approach (within 11.5%) the tensile strength of neat HDPE and exceed it in surface hardness makes the material a genuine candidate for engineering components that do not required to bear peak structural loads but need to resist surface damage and moderate mechanical stress.

Taken together, the benchmark comparison leads to a straightforward practical recommendation: for applications where surface hardness is a primary requirement and tensile strength needs are moderate, the 10 wt% jute + 10 wt% sisal hybrid (specimen C) is the preferred composition for the substrate. For applications where tensile strength is the governing criterion, the 10 wt% jute + 5 wt% sisal hybrid (specimen D) is the better choice. Neither single-fiber composite — 15 wt% jute or 15 wt% sisal alone — can compete with these hybrid configurations on either mechanical metric, which constitutes perhaps the clearest argument of this entire study for the engineering value of hybridization over single-fiber reinforcement.

FUTURE SCOPE

This study investigation establishes a reliable experimental foundation for jute–sisal/HDPE hybrid composite research. The following points identify specific directions in which this work can be meaningfully extended:

1. Mechanical Engineering — Extended Property Evaluation: Future studies should characterize flexural strength, flexural modulus, impact strength (Charpy and Izod), interlaminar shear strength, and compressive strength across the same fiber weight fractions to enable a complete mechanical property map.

2. Materials Science — Fiber Length and Orientation: Systematic variation of fiber length (2–20 mm) and examination of fiber orientation — random, unidirectional, or woven — on anisotropic mechanical behavior should be investigated.

3. Surface Engineering — Advanced Treatments: Silane coupling agents, acetylation, benzoylation, and enzyme-based treatments should be compared with the NaOH treatment used here to potentially eliminate the dewetting-induced debonding identified as the primary failure mechanism.

4. Polymer Science — Alternative Matrix Materials: Polypropylene (PP), bio-based polylactic acid (PLA), and recycled post-consumer HDPE should be explored as alternative matrices to enhance environmental credentials and align with circular economy principles.

5. Environmental Science — Life Cycle Assessment: A formal LCA quantifying the carbon footprint, energy consumption, water usage, and biodegradability of the hybrid composite relative to conventional glass fiber reinforced polymers has not been conducted and would support science-based environmental claims.

6. Thermal Engineering — Thermal Stability: TGA, DSC, and DMA should be carried out to determine the onset decomposition temperature, glass transition temperature, and storage modulus as functions of fiber content.

7. Civil Engineering — Water Absorption and Durability: Quantitative water absorption study under ASTM D570 correlated with tensile strength and hardness retention, plus long-term UV, weathering, and salt-spray durability tests, are needed.

8. Manufacturing Engineering — Alternative Processing: Compression molding, twin-screw extrusion, resin transfer molding (RTM), and 3D printing of fiber-filled HDPE filaments should be examined and optimized using DOE methods.

9. Nanotechnology — Nano-Filler Addition: Small weight fractions (0.5–3 wt%) of nanoclay, carbon nanotubes, graphenenanoplatelets, or cellulose nanocrystals should be incorporated to close the tensile strength gap between the hybrid composite and neat HDPE.

10. Biomedical Engineering — Structural Aids: Cytotoxicity and biocompatibility of alkali-treated jute–sisal/HDPE composites should be assessed against healthcare safety thresholds for applications such as splints, orthotics, and rehabilitation equipment.

11. Computational Mechanics — Finite Element Modelling: FEM models validated against the experimental data in this study should be developed to predict the stress distribution and failure loads under tensile, compressive, and flexural conditions.

12. Tribology — Wear and Friction Behavior: Wear rate, specific wear, and coefficient of friction under dry sliding conditions should be investigated using a pin-on-disc tribometer to establish whether the measured hardness advantage translates into improved wear resistance.

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