

Production of Injection Moulded Natural Fiber Reinforced Hybrid Composites and Assessment of Hybridization's Effect on Mechanical Properties

Gobind^{1*}, Tejeet Singh²

Abstract

Over the past two decades, rising environmental awareness, public concern over waste, and stricter government regulations have encouraged companies to reduce their reliance on petroleum-based fuels and products. Consequently, there is a clear need to find sustainable, eco-friendly substitutes for the materials currently in use. This shift has renewed attention on renewable resources and sparked wider interest in advanced composites and green materials research. With this in mind, the present work develops a hybrid composite reinforced with three different natural fibers in a single matrix and studies its mechanical behavior. The injection moulding process parameters were optimized using the Taguchi technique, and ANOVA was applied to identify the parameter with the strongest influence on the desired performance. This study investigated how varying quantities of three natural fibers influence the flexural strength, flexural modulus, and impact strength of hybrid composites. The findings show that injection moulding is an effective route for producing hybrid composites by reinforcing HDPE with three different natural fibers. The flexural strength and modulus of the hybrid composite improved with fiber reinforcement, whereas the impact strength of all fabricated hybrid composites was found to be lower than that of neat HDPE (13.5 J/m), with a more pronounced reduction observed at higher fiber loading (18 wt. %). Statistical analysis indicated that fiber loading (Wt. %) was the parameter with the greatest effect on the mechanical properties of these composites.

Keywords: Hybrid composite, flexural strength, flexural modulus, impact strength, HDPE.

INTRODUCTION

Composite materials have advanced rapidly in recent years, and there has been a clear surge in research aimed at replacing synthetic reinforcements in plastic composites with natural fibers. To keep up with growing industrial demand, researchers continue to develop new hybrid materials that are now used across construction, aerospace, automotive, and several other sectors [1-3]. These materials have become essential because they offer notable advantages over conventional ones. When two or more

materials are combined while keeping their macrostructure intact, the result is a material that can be tailored to perform better than either of its constituents on its own. Composites have drawn researcher attention because of qualities such as light weight, corrosion resistance, high fatigue strength, and quicker assembly compared with traditional materials. Public expectations around products made from renewable resources have also become stricter in recent years. Consumer interest in eco-friendly goods is being shaped by social pressure, new recycling rules, green marketing, and changing attitudes. Composite materials, in particular, are being designed and redesigned with

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the aim of bringing new products to market in a sustainable and responsible way while also improving the older ones [4]. A composite normally consists of a reinforcement (fibers, particles, flakes, or fillers) embedded within a matrix (polymer, metal, or ceramic). The matrix holds the reinforcement in place and gives the part its shape, while the reinforcement carries most of the load and improves the mechanical performance of the matrix [5]. When designed properly, the resulting composite is stronger than either of its individual components. In green composites, natural fibers are usually chosen as the reinforcement. To improve mechanical properties further, two or more types of natural fibers can be combined within the same matrix to form a new hybrid composite, a process known as hybridization [6]. The benefits of placing two different fiber types in a single matrix have been reported in many earlier studies. Among the useful features, composites bring are low weight, good mechanical and chemical resistance, low maintenance, and design flexibility [7, 8].

As limited resources continue to deplete, researchers are exploring alternative methods for producing biomass. One growing trend is the technical replacement of cheaper or low-value products with high-performance materials [9, 10]. The Addition of natural biomass to polymer composites meets the current industrial needs while remaining cost-effective and environmentally friendly [11, 12]. Much of the research has focused on the thermo-mechanical performance of plant fibers, which have drawn attention as reinforcements for the polymer matrices. Studies have shown that plant fibers can improve the mechanical behavior of bio-composites built on a thermoplastic matrix, including their stiffness and Young's modulus [13, 14].

Growing environmental awareness, public concern, worldwide waste problems and waste management regulations introduced by governments are some of the main drivers behind the push for advanced hybrid composites.

The aims of the current study are summarized below:

- To use an injection moulding machine to produce a hybrid composite made of jute, sisal, and hemp fibers bonded with high density polyethylene (HDPE).
- To examine how hybridization affects the flexural strength, flexural modulus, and impact strength of the hybrid composite by optimizing the injection moulding process parameters.
- To find statistically meaningful links between mechanical behavior and process parameters using ANOVA and the Signal-to-Noise Ratio (SNR).

The main objective of this study was to develop a hybrid green composite by examining HDPE reinforced with three natural fibers, fabricated through injection moulding. This study tests and analyzes how varying the percentage of fibers and the injection pressure affects the mechanical properties, marking a fresh contribution to the field. Producing bio-composites from agricultural waste holds promise for advancing sustainable materials, supporting the circular economy, and disposing of biomass waste in a useful manner.

This paper follows the standard academic structure; Section 2 reviews the relevant literature; Section 3 explains the methodology; Section 4 presents the empirical findings and results; Section 5 outlines the applications of the fabricated composites; Section 6 discusses the implications of the research; Section 7 presents the conclusions; Section 8 covers the future scope.

LITERATURE REVIEW

Hybridization of natural fibers has been widely used to produce green composites that are biodegradable and ecologically friendly, while also showing improved mechanical behavior. Several researchers have applied techniques such as the Taguchi design, hybrid algorithms, and simulation-based methods to identify the key factors and determine the best processing conditions for fabricating green hybrid composites.

Idicula et al. (2005) [15] reported that a polyester composite reinforced with randomly arranged short banana and sisal fibers displayed favorable hybrid effects on its mechanical properties. The tensile properties of a wood-flour-reinforced polypropylene composite improved when kenaf fibers were added. Gbenga Ekundayo, Sam Adejuyigbe (2019) [16] investigated that sisal and jute fibers are continuous with high specific tensile, stiffness, and impact strength coupled with their controlled anisotropic properties, which can be developed and manufactured into structural beams, columns, etc., for structural applications and replacing synthetic composites in building and bridge constructions. Ilyas et al. (2021) [17] estimated the best injection moulding settings for minimum shrinkage using a Taguchi DOE approach. The packing pressure was the most influential factor for polypropylene (PP), followed by the injection pressure, melt temperature, and packing time. Venkateshwaran and Elaya Perumal (2012) [18] studied the effect of hybridizing woven jute and banana fabrics in an epoxy resin (LY556) matrix on the mechanical and water absorption properties of the resulting composites. According to Kumar and Singh (2015) [19], the properties of HDPE filled with wood fibers improve as the fiber size increases. The addition of wood fibers enhances both the mechanical and physical characteristics of the biocomposite. However, as the fiber concentration increased, the strength began to decrease, leading to an uneven stress distribution and a decline in elongation and impact resistance. Ghernaout (2024) [20] noted that YF/HDPE biocomposites could serve as affordable and sustainable substitutes for conventional materials in many applications. Owing to their load-bearing ability and recyclability, this type of biocomposite is a practical option for sporting goods, eco-friendly construction materials, and automotive interior trim. Yadav et al. (2021) [21] highlighted the rising interest in natural-fiber-filled polymer matrices as substitutes for synthetic composites, pointing to lower non-renewable resource use and reduced environmental impact. They also highlighted attention to the potential of bio-nano composites for food packaging because of their improved barrier and antibacterial properties. Chen et al. (2023) [22] applied Taguchi and ANOVA and identified ambient and melting temperature as the main causes of warpage in PET preforms, lowering overall warpage by 7.72% with the optimized values. In a similar way, Guo et al. (2024) [23] put forward an intelligent optimization approach (DNN-GA-MCS) to improve the structural performance of carbon-fiber-reinforced polymer. Their method achieved a noticeable gain in strain energy and reduced weight by 16.67% compared with traditional panels. Haris et al. (2022) [24] reinforced HDPE with jute, sisal, and hemp, showing the promise of multi-fiber hybrid composites as a green and recyclable option for automotive, sports, and building uses. Along the same lines, Dezfooli et al. (2024) [25] combined Taguchi, FAHP, and TOPSIS with FEA and ANN for validation, cutting shrinkage and sink marks down to very low levels. Zhang et al. (2025) [26] optimized injection moulding (IM) conditions for the rear cover of an LCD monitor using Taguchi design and software tools such as Moldflow, MINITAB, and MATLAB. The Taguchi method picked out four key parameters with regression errors below 2.5%, and its limitation of yielding only preselected combinations was overcome by adding Particle Swarm Optimization (PSO), which pushed warpage errors below 3.5%. In a similar manner, Aslam et al. (2025) [27] used the Taguchi L27 orthogonal array to improve PET perform moulding in industry, achieving a 4.75% drop in warpage and a 2.05% reduction in weight. These studies confirm that Taguchi-based DOE, especially when paired with verification tests or hybrid approaches, lowers moulding defects and raises product quality. Abdulrahman et al. (2025) [28] applied a Taguchi L9 design together with Solid Works Plastic simulations to optimize the moulding of HDPE-banana fiber composites. Their results showed effective cavity filling and reduced fiber degradation, pointing to the value of Taguchi methods for processing biopolymer composites.

The current literature shows extensive research on extracting fibers from agricultural waste for use in polymer biocomposites. However, the use of jute, sisal, and hemp together as fillers in biocomposites is limited. To date, no study has examined the possible benefits of varying the proportions of these three natural fibers within an HDPE matrix. Most researchers have worked on a single reinforcement in a matrix, and very few studies have been conducted on combining two or three natural fibers within one matrix. A great deal of research has been conducted on natural fiber reinforcement in polypropylene, but research on HDPE reinforced with natural fibers remains limited. Therefore, there is a clear need to fabricate a hybrid material with HDPE reinforced by three different fibers and to study how hybridization affects the mechanical behavior while also tuning the injection moulding parameters.

METHODOLOGY

Materials Selection

High-density polyethylene (HDPE) was selected as the thermoplastic matrix, while three natural fibers jute, sisal, and hemp acted as the reinforcing agents. HDPE was procured in pellet form, and all three fibers were prepared as short fibers to ensure uniform dispersion during processing. To create the hybrid composite, the three natural fibers were reinforced with HDPE. The fibers were sourced from Chandra Prakash & Company in Jaipur, Rajasthan, while Batra Polymers in Ludhiana, Punjab, India supplied the HDPE.

Fiber Surface Treatment

Before composite fabrication, the fibers were treated to improve adhesion at the fiber-matrix interface. After treatment, the fibers were neutralized, dried again, and stored in sealed containers until use to protect them from moisture. Alkaline treatment was carried out on the three fibers separately before fabrication. The physical treatment involved cleaning the fibers thoroughly with tap water, drying them in the sun at 44°C in June, and then drying them for a full day at 80°C in an electric oven to remove all remaining moisture. After oven drying, the fibers were chopped into short pieces between 5 and 10 mm long.

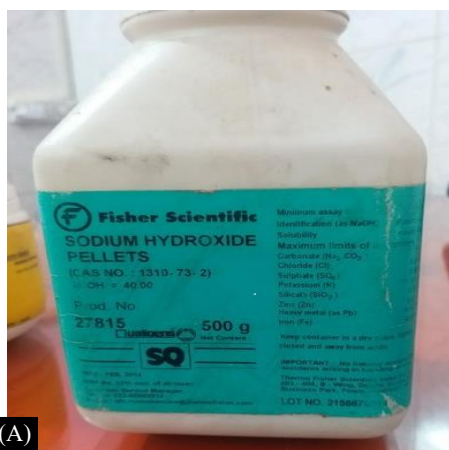
Alkaline Treatment of Fibers

When making composites based on natural fibers, the surface bonding and chemical structure of the fiber plays a crucial role. A high level of surface bonding between the reinforcement and matrix is preferred to achieve better flexural and impact properties. Therefore, for this, many researchers have investigated ways to treat fibers to improve their bonding with the matrix [29-31]. The amount and properties of each component, along with the type of interfacial region between the matrix and reinforcement, can shape the mechanical properties of the resulting composites.

A sodium hydroxide (NaOH) solution was used to treat the jute (J), sisal (S), and hemp (H) fibers. Maya Chemtech India Private Limited in New Delhi supplied the NaOH in pellet form as shown in Figure 1A.

A bucket was filled with 15 litres of water and 900 gms of NaOH pellets. The pellets were dissolved in water to form a 6% NaOH solution as shown in Figure 1B. Each of the three short fibers was soaked in the NaOH solution for a full day as shown in Figure 1C at room temperature [32].

Afterwards, The treated fibers were washed separately with distilled water several times to remove the excess NaOH until a pH value of 7 was reached. Finally, the short fibers were spread evenly across trays and dried in a hot air oven as shown in Figure 1D, at 90°C for 24 hours respectively till they reached a constant mass.

**(A)****Figure 1.** NaOH Pellets.**(B)****Figure 1.** Preparation of NaOH pellets solution.

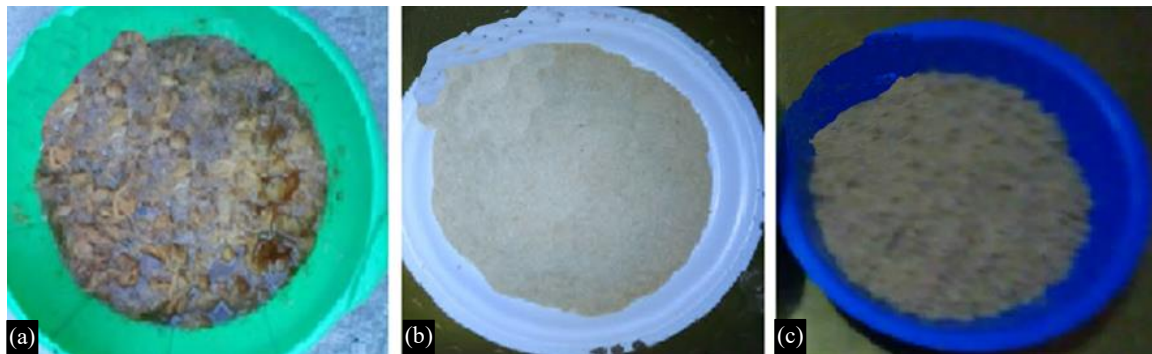


Figure 1(C). (a) Jute (b) Sisal and (c) Hemp Fibers Immersed in NaOH pellets solution.



Figure 1. Treated fibers drying in oven.

Coupling Agent

One of the primary challenges in developing natural fiber reinforced composites is the contrasting surface properties of the constituent materials. Natural fibers are hydrophilic, whereas HDPE, a non-polar polymer, is hydrophobic. Due to this mismatch, the fiber and matrix fail to bond adequately at the interface, which ultimately results in weakened mechanical properties in the final composite. Therefore, the S-69 silane coupling agent was blended into the mixture at 1 wt. % during the batch preparation stage to strengthen the fiber–matrix interface.

S-69 operates on a bifunctional principle — one reactive group of the compound attaches itself to the hydroxyl (-OH) sites available on the fiber surface, while the other reactive group establishes a connection with the surrounding HDPE matrix. This results in a stable molecular linkage across the interface that allows better load and stress transfer between the fiber and matrix during mechanical loading. Maintaining the silane content at 1 wt. % was a conscious decision. When silane is added beyond its effective threshold, it tends to pile up as non-reactive layers over the fiber surface rather than contributing to bonding, which can weaken the composite. At the selected proportion, S-69 was effective in improving fiber surface wettability, preventing fiber clustering, and achieving satisfactory interfacial adhesion among jute, sisal, and hemp fibers dispersed within the HDPE matrix. The silane was purchased from Mahaveer chemical private limited, New Delhi.

Composite Fabrication

The treated short fibers were dry-blended with HDPE pellets at three fiber weight fractions 6 wt. %, 12 wt. %, and 18 wt. % for each fiber type. The blended material was then processed in an injection moulding machine to produce composite specimens for mechanical testing. The conditions listed in Table 1 were followed during fabrication. Three parameters were chosen for the study: fiber type, fiber loading, and injection pressure. Each parameter had three levels: J (Jute), JH (Jute & Hemp), and JSH (Jute, Sisal & Hemp); 6, 12, and 18 wt. %; and 40, 50, and 60 Bar respectively. The experiments were carried out using an L9 orthogonal array, which set the order of the runs. MINITAB software version 18 was used to convert all the experimental results into a Taguchi analysis. The fiber weight percentage and the injection pressure were varied according to the fabrication plan.

Table 1. Levels of design parameters.

S.N.	Selected parameter	Level 1	Level 2	Level 3	Unit
1	Fiber Type	J	JH	JSH	-
2	Fiber Loading	6	12	18	Wt. %
3	Injection Pressure	40	50	60	Bar

After the fibers were dried in the oven, they were packed in plastic bags to keep them away from moisture. Before the material entered the injection moulding machine, batches of one kilogram each were prepared in line with Table 1. The weight of each batch was checked on a weighing machine. The prepared samples were placed in plastic bags and labelled with a permanent marker. Once all the batches had been weighed, they were mixed separately with a stick in a plastic bucket. During mixing, 1% silane by weight (the coupling agent S-69, used to help the fibers bond with the HDPE matrix) was added to each batch. The material was now ready for producing composite samples. The specimens for flexural and impact testing were made on an injection moulding machine (Electronica 70-90 ton, model 1656) at CIPET, Amritsar, Punjab. To prepare the specimens one by one, the dried material batches were fed into the machine through a hopper. The batches were forced into an insert mould chamber where they cooled and set into the mould shape. The specimen size and geometry followed ASTM D790 for flexural strength and flexural modulus and ASTM D256 for impact strength. In total, nine composites were moulded with different fiber reinforcements at varying weight percentages in HDPE, injected at different pressures. For these nine composites, 27 specimens were produced (three per composite configuration). Each test was repeated three times to obtain mean values, ensuring the quality of the developed composite could be optimized.

Design of Experiment

The Taguchi statistical approach was used to determine the best combinations of the chosen parameters, the effect of those parameters on the mechanical properties, and the most influential factor among them. The Taguchi method built a statistically efficient experimental plan based on an L9 orthogonal array, with three parameters at three levels each: (i) fiber type (Jute, Sisal, and Hemp), (ii) fiber loading (6 wt. %, 12 wt.%, and 18 wt.%), and (iii) Injection Pressure (40 Bar, 50 Bar, and 60 Bar). This setup allowed all parameter combinations to be evaluated in nine experimental runs, saving material while maintaining statistically valid result. The Taguchi strategy is a fairly economical and straight forward method for handling experimental problems. Using it, researchers can significantly reduce the time and money required to conduct trials. Because experimental research procedures are usually expensive and slow, achieving study goals with the fewest possible runs is important. The Taguchi technique offers an efficient and systematic test procedure for choosing the best parameter settings to achieve the desired performance, manage costs, and save time. Using this approach, the present study captured the effects of the chosen parameters, namely, fiber type, fiber loading, and injection pressure, on the mechanical properties of the hybrid composites.

Statistical Analysis - ANOVA and S/N Ratio

Signal-to-noise (S/N) ratios were calculated for each experimental run using the 'larger-the-better' criterion, because higher values of flexural strength, flexural modulus, and impact strength are preferred. Analysis of Variance (ANOVA) was then performed to quantify the percentage contribution of each control parameter to the variation observed in the mechanical responses, with statistical significance assessed at a 95% confidence level.

List of Abbreviations

The list of abbreviations used in the study is shown in Table 2.

Mechanical Characterisation

Three mechanical properties were measured on the fabricated specimens: flexural strength and flexural modulus through three-point bending tests in line with ASTM D790, and impact strength using an Izod impact tester according to ASTM D256. At least three specimens were tested for each experimental condition, and the average values were reported to ensure reproducibility and statistical reliability of the results.

Table 2. List of abbreviations.

HDPE	High density polyethylene
J	Jute
H	Hemp
S	Sisal
JHD	Jute–HDPE Composite
JHHD	Jute,Hemp–HDPE Composite
JSHHD	Jute,Sisal,Hemp–HDPE Composite
NaOH	Sodium Hydroxide
pH	Potential of Hydrogen
wt. %	Weight Percentage
S-69	Silane (coupling agent)
Gpa	Gega Pascal
MPa	Mega Pascal
ANOVA	Analysis of Variance



Figure 2. Flexural sample prior to testing.

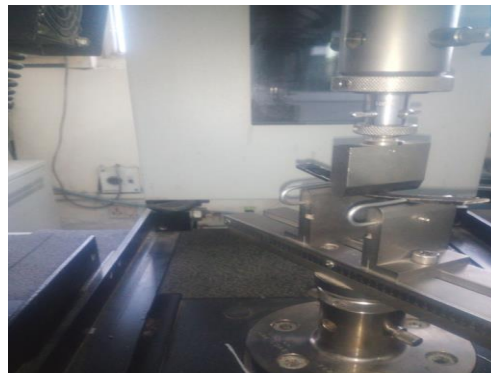


Figure 3. Flexural test loading arrangements.

Testing for Flexural Strength and Flexural Modulus

Flexural specimen samples measuring $50 \times 12.40 \times 3.30 \text{ mm}^3$ were produced using an injection-moulding machine. Flexural tests were performed according to ASTM D790, using a standard material testing setup with a crosshead speed of 1.50 mm/min. The flexural properties of the composites were measured using three-point bending tests. The composite specimens before and after the flexural testing, along with the loading arrangement, are shown in Figures 2 and 3, respectively. The tests were repeated thrice for each composite formulation, and the average values were reported.

Each specimen was conditioned in an environmental test chamber (KASKO Industries, Pune) for 40 hrs at 23°C and 50% relative humidity before testing.

Impact Evaluation of Manufactured Specimens

The test specimens were prepared in line with ASTM D256. Each impact test specimen was tested using an Izod impact tester. First, a manual notch cutter was used to cut a 2.5 mm notch at a 45° angle (Figure 5). Impact testing measures a material's resistance to sudden loading. It can show how a known material specimen responds to a stress that is applied abruptly, such as a shock. The testing equipment used was a Tinius Olsen Model Impact 104 pendulum impact testing machine (Figure 4). Figure 6 shows the impact test specimens. When the impact energy hammer struck different specimens, the measured impact energy values were read directly from the electronic panel. For each composite type, the test was carried out three times and the average value was recorded.

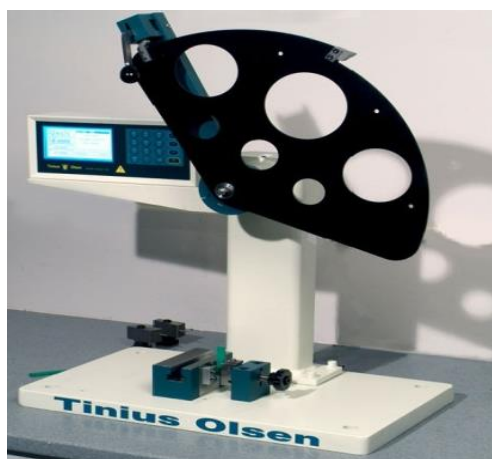


Figure 4. Izod impact tester

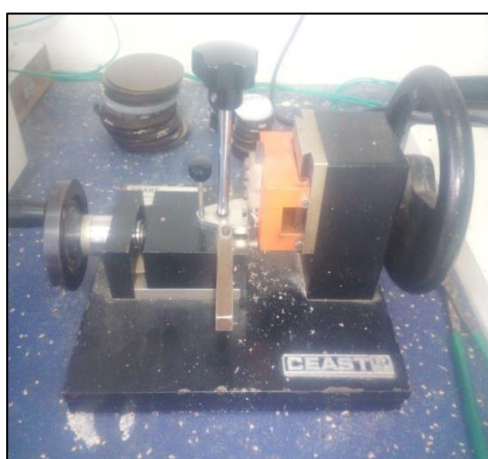


Figure 5. Notch cutter



Figure 6. Impact testing samples.

Table 3. Flexural properties of composites.

S.N.	A	B	C	Flexural strength (MPa)	Flexural modulus (GPa)
1	1	1	1	18.37	1.65
2	1	2	2	18.91	1.76
3	1	3	3	17.86	1.39
4	2	1	2	19.32	1.72
5	2	2	3	19.37	1.93
6	2	3	1	18.86	1.54
7	3	1	3	20.49	2.51
8	3	2	1	21.62	2.73
9	3	3	2	19.81	2.29

RESULTS

Composites' Flexural Properties

Flexural strength is associated with the bending behavior of materials. To increase the flexural strength of a material, new composite with improved bending performance must be developed. The differences in the flexural characteristics of the various composites are listed in Table 3. The flexural strength trends for all the produced composites, JHD, JHHD, and JSHHD, are shown in Figure 7. From Table 3, the flexural strength of the JHD composite ranged from 17.86 to 18.91 MPa, that of the JHHD composite from 18.86 to 19.37 MPa, and that of the JSHHD composite from 19.81 to 21.62 MPa.

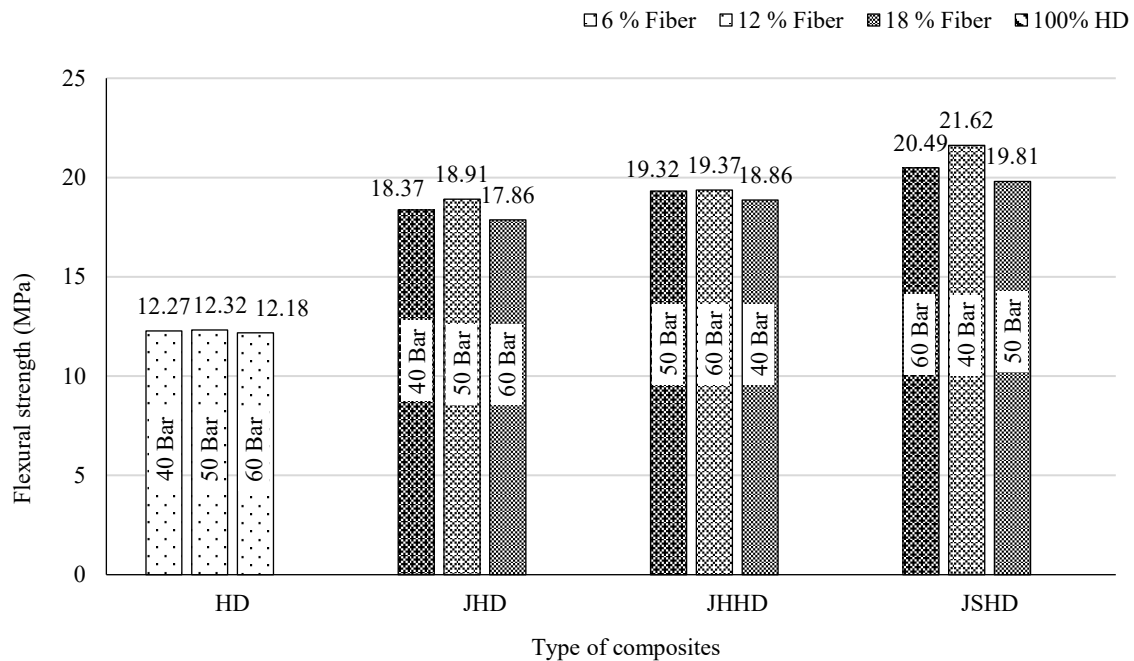


Figure 7. Flexural strength of composites.

The flexural strength of the JHD composites increased when an additional 12 weight percent of fiber was added, and the injection pressure was increased from 40 to 50 Bar. However, when the injection pressure was increased from 50 to 60 Bar and the fiber content was increased to 18 wt. %, the flexural strength dropped. A similar pattern was observed for the JHHD composite. The highest flexural strength was achieved at 12 wt.% fiber loading. Furthermore, as the fiber weight percentage increased, the flexural strength of the composite decreased. The hybrid JSHHD composite also exhibited an increase in flexural strength up to 12 wt.% at 40 Bar. The improved flexural strength of the JSHHD composite up to 12 wt. % fiber loading is likely due to good interfacial interaction between the fibers and the matrix. Compared with pure HDPE, the flexural strength of the produced composites improved slightly with respect to the fiber weight percentage. Increasing the fiber loading up to 12 wt. % improves flexural strength, but pushing it further to 18 wt. % causes the flexural strength to fall.

Figure 8 shows the obtained flexural modulus values. The flexural modulus decreased when the fiber content was increased to 18 wt. %. Adding 12 wt. % fiber and raising the injection pressure from 40 to 50 Bar increased the flexural modulus of JHD composites. However, the flexural modulus decreased when the injection pressure was increased from 50 to 60 Bar, and the fiber concentration was increased to 18 wt.%. The hybrid JHHD and JSHHD composites behaved in a comparable manner, with the highest flexural modulus measured at 12 wt. % fiber loading. As the fiber weight fraction increased further, the flexural modulus decreased.

Composites' Impact Strength

Figure 9 shows the various impact strength values calculated for all the produced composites and pure HDPE. The values listed in Table 4 and shown in Figure 9 indicate the impact strength of the different composites. At an injection pressure of 50 Bar, the impact strength of the pure HDPE matrix was 13.5 J/m, which was higher than that of any of the produced composites.

The impact strength of the JHD composite ranged from 6.64 to 8.96 J/m. When the fiber loading reached 12 wt. %, the impact strength of JHD composites rose; when it was pushed to 18 wt.%, the impact strength fell.

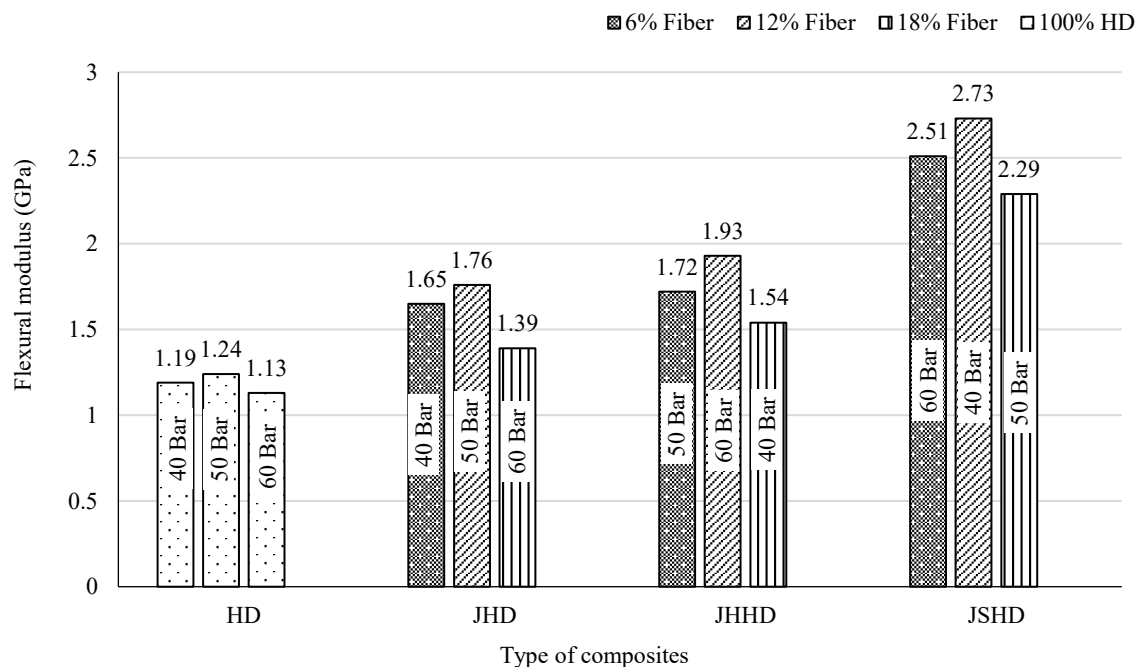


Figure 8. Flexural modulus of composites.

Table 4. Impact strength of composites.

S.N.	A	B	C	Impact strength (J/m)
1	1	1	1	8.17
2	1	2	2	8.96
3	1	3	3	6.64
4	2	1	2	8.21
5	2	2	3	9.98
6	2	3	1	6.8
7	3	1	3	9.35
8	3	2	1	10.05
9	3	3	2	7.52

A similar trend was observed for the JHHD composites, where the impact strength ranged between 6.8 and 9.98 J/m and reached a maximum of 9.98 J/m at an injection pressure of 60 Bar with 12 wt. % fiber loading. The impact strength of the JSJHD hybrid composites ranged from 7.52 to 10.05 J/m, with a peak value of 10.05 J/m at 12 wt.% fiber loading.

The impact strength of the JHD, JHHD, and JSJHD composites increased when fiber loading reached 12 wt. % and dropped when it was raised to 18 wt.%, but in all cases it stayed below the value for 100% HDPE. The impact strength of all fabricated hybrid composites was found to be lower than that of neat HDPE (13.5 J/m), with a more pronounced reduction observed at higher fiber loading (18 wt. %), attributed to stress concentration at the fiber–matrix interface under sudden loading conditions.

Effect of Selected Parameters, ANOVA and Significance of Parameters

Effect on Flexural Strength

The Taguchi L9 orthogonal array was used to assess the effects of the chosen parameters on the flexural strength and modulus of the composites. Table 5 lists the experimental data on flexural strength. The response levels of each experiment are shown in the Table as R1, R2, and R3, respectively.

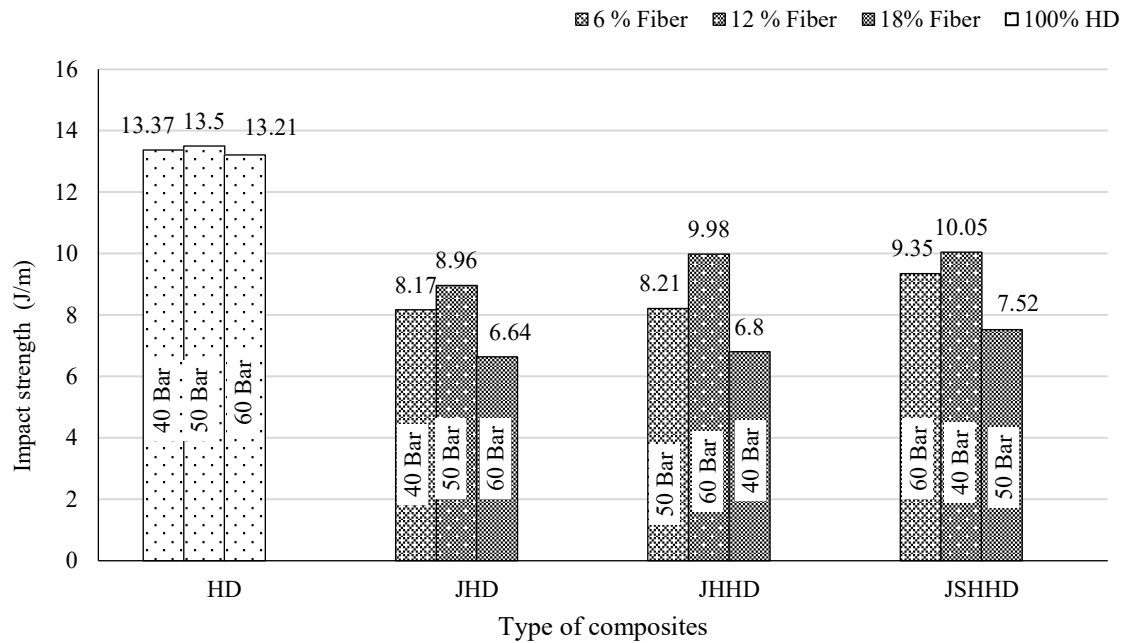


Figure 9. Developed composite impact strength.

Table 5. The flexural modulus response and flexural strength.

Exp.	A	B	C	Flexural Strength (MPa) (Response)			FS Avg.	Flexural modulus (GPa) (Response)			FM Avg.
				R_1	R_2	R_3		R_1	R_2	R_3	
1	1	1	1	18.70	18.17	18.23	18.37	1.64	1.62	1.68	1.65
2	1	2	2	18.83	19.15	18.74	18.91	1.69	1.82	1.77	1.76
3	1	3	3	17.77	17.82	17.98	17.86	1.22	1.52	1.43	1.39
4	2	1	2	19.42	19.17	19.38	19.32	1.72	1.82	1.61	1.72
5	2	2	3	19.48	19.27	19.36	19.37	1.97	1.95	1.87	1.93
6	2	3	1	19.13	18.83	18.62	18.86	1.54	1.51	1.57	1.54
7	3	1	3	20.88	20.64	19.96	20.49	2.67	2.32	2.55	2.51
8	3	2	1	21.36	21.83	21.68	21.62	2.94	2.86	2.39	2.73
9	3	3	2	20.12	19.57	19.74	19.81	2.16	2.21	2.49	2.29

The S/N data in Table 6 and the mean values in Table 7 were used to evaluate the mean and S/N ratios of the responses. The analysis showed that B, the fiber weight percentage, had the largest delta value of 0.93 and the highest rank of 1, making it the most influential parameter for flexural strength. Fiber type (A) was ranked second. Figures 10 and 11 show the mean flexural strength values for each chosen parameter at the three levels for the mean data and S/N ratio, respectively.

As shown in Figure 10, the fiber weight percentage at level 2 had the strongest effect on flexural strength. Therefore, the hybrid JSHHD composite exhibited the highest flexural strength among the composites developed. The flexural strength reached its peak at the second level of fiber loading (B2-12%), first level of injection pressure (C1-40 Bar), and third level of fiber type (A3-JSH). The S/N data analysis in Figure 11 shows the same trend for the maximum flexural strength as the ANOVA results.

Table 8 lists the significant and non-significant factors affecting flexural strength. The results show that point C, which stands for injection pressure, is a non-significant parameter for flexural strength, while points A and B fiber type and fiber weight percentage are significant.

Table 6. Flexural strength response Table S/N.

Level	A	B	C
1	25.74	25.36	25.83
2	25.99	25.66	25.73
3	25.20	26.29	25.32
Delta	0.79	0.93	0.51
Rank	2	1	3

Table 7. Response table for average of flexural strength.

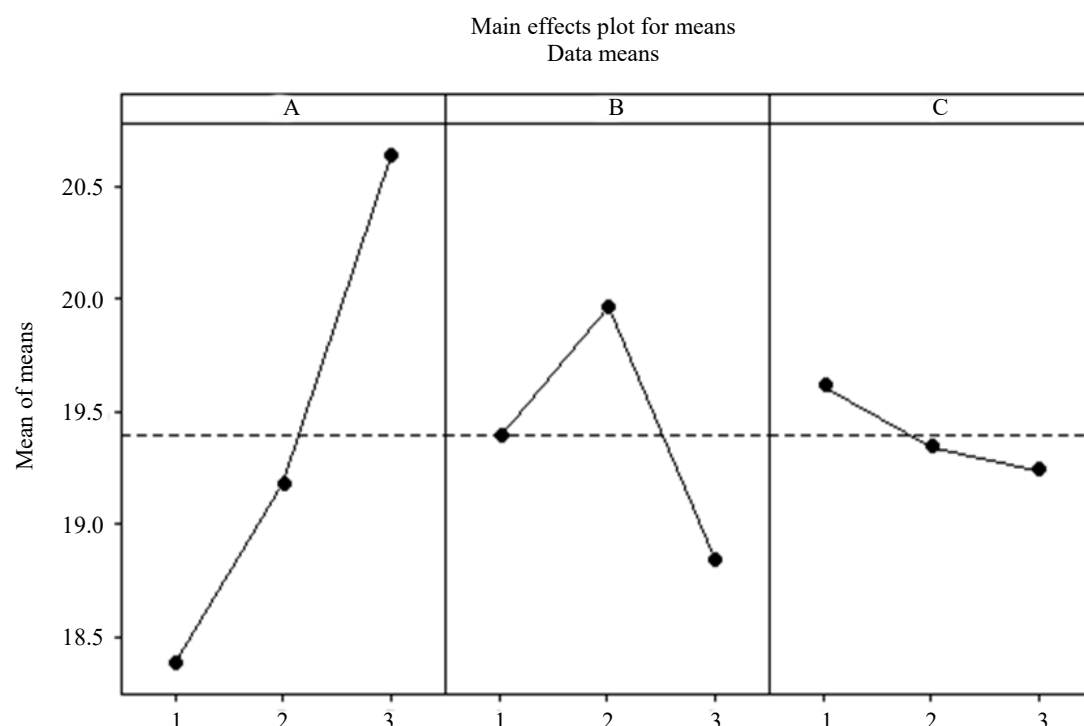
Level	A	B	C
1	19.39	17.38	19.62
2	19.97	19.18	19.35
3	17.85	20.64	18.24
Delta	2.12	3.26	1.38
Rank	2	1	3

The flexural strength residual plot (Figure 12) shows that all residuals in the normal probability plot lie close to the straight line, indicating that errors in the data acquisition were negligible.

Effect on Flexural Modulus

Tables 9 (S/N ratios) and 10 (mean values) present the response data for the flexural modulus, again using the 'larger-is-better' criterion.

From Table 9, the fiber weight percentage (B) takes the first rank, with the highest delta value of 3.93. Fiber loading had the strongest effect on the flexural modulus, as shown by the rankings and delta values of the parameters. The same conclusion is confirmed by the ranks and delta values in Table 10.

**Figure 10.** Impact of specific parameters on developed composites' flexural strength (mean data).

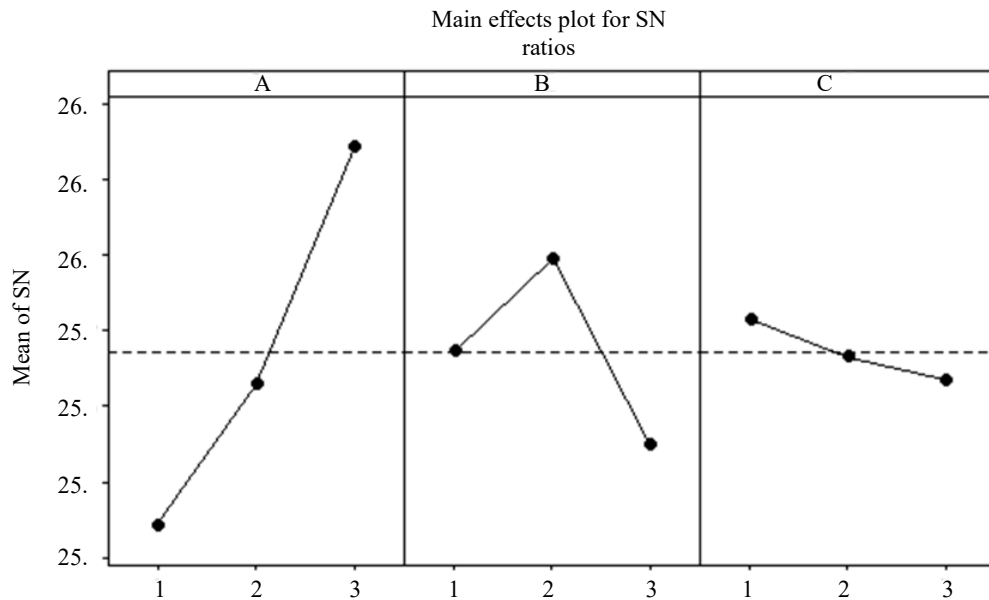


Figure 11. Effect of particular parameters on the flexural strength of different composites (S/N Data).

Table 8. ANOVA for flexural strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	68.578	68.578	33.494	4.45	0.027
B	2	110.51	110.51	54.365	7.13	0.003
C	2	40.743	40.743	19.627	2.68	0.089
Error	20	148.834	148.834	6.519		
Total	26	368.66				

Residual plots for flexural strength

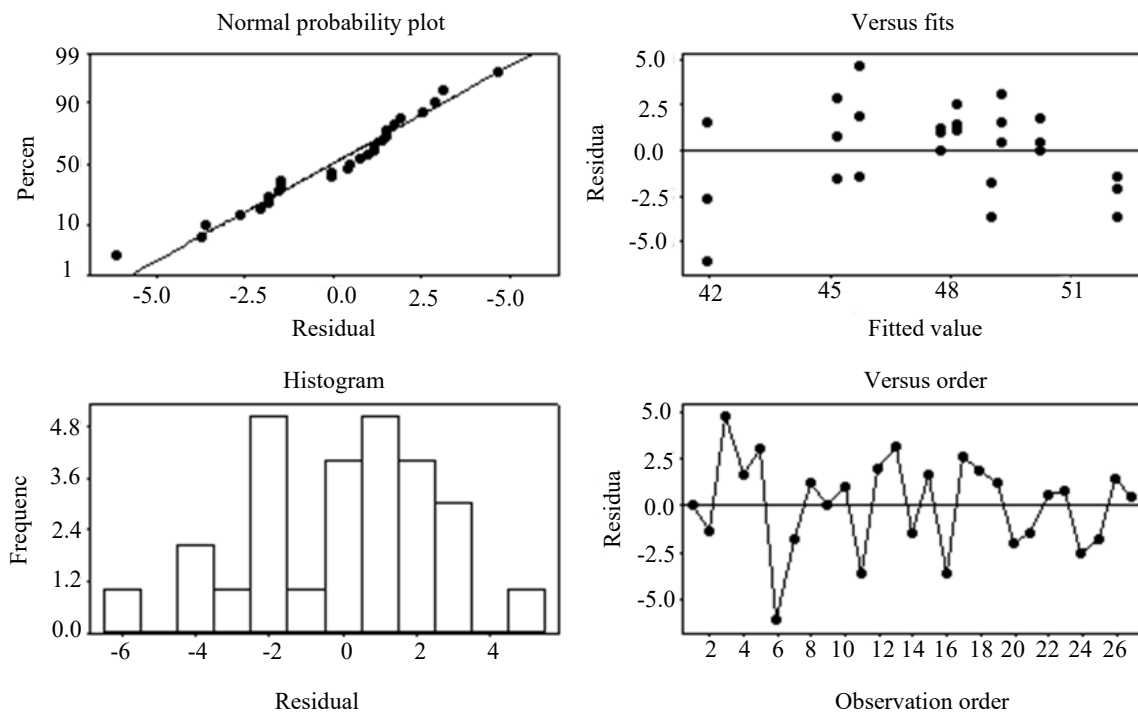


Figure 12. Impact of specific parameters on developed composites' flexural strength (residual).

Table 9. Response table for flexural modulus S/N ratio.

Level	A	B	C
1	5.68	4.04	5.60
2	6.44	4.72	5.54
3	4.60	7.97	5.52
Delta	1.84	3.93	0.08
Rank	2	1	3

Table 10. Average flexural modulus response table.

Level	A	B	C
1	1.96	1.60	1.97
2	2.14	1.73	1.92
3	1.74	2.51	1.94
Delta	0.40	0.91	0.05
Rank	2	1	3

Figure 13 shows that the highest flexural modulus comes from the third level of fiber type (A3-JSH) and, the second level of fiber loading (B2-12 wt. %), and the first level of injection pressure (C1-40 Bar). The S/N data analysis points to the same results. Figure 14 shows the Effect of Selected Parameters on Flexural Modulus (S/N Data).

Table 11 shows that points A and B fiber type and fiber loading are significant parameters for flexural modulus, while point C, injection pressure, is non-significant.

The flexural modulus residual plot (Figure 15) shows that all residuals lie close to the straight line in the normal probability plot; therefore, the data acquisition errors are negligible.

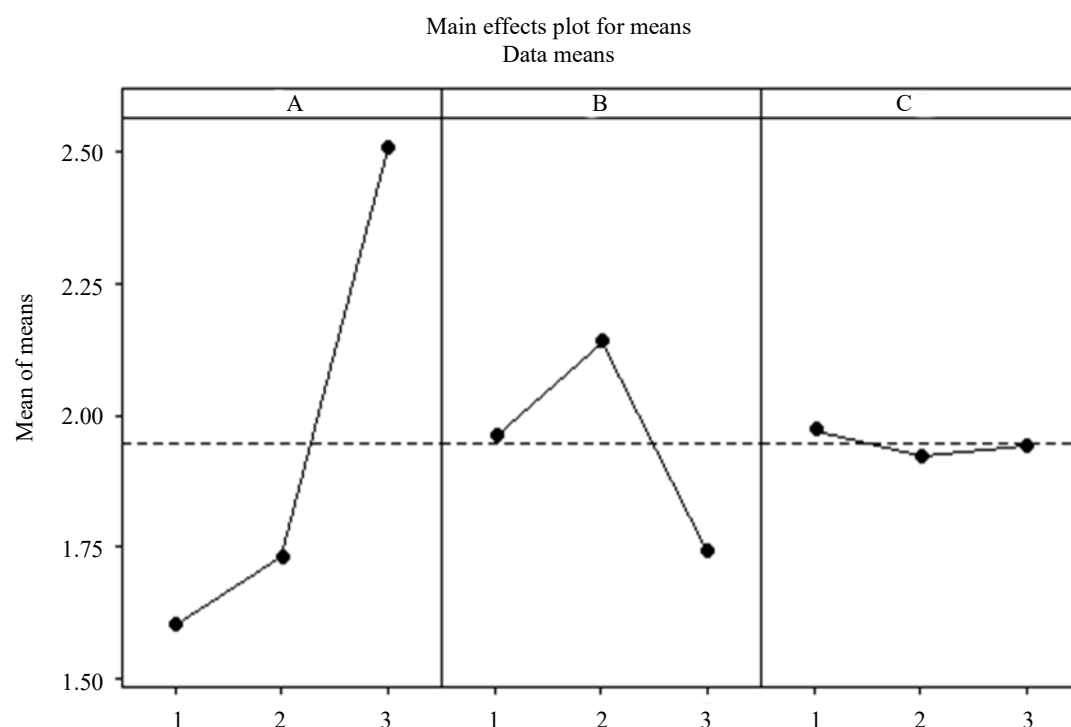


Figure 13. Effect of selected parameters on flexural modulus (Mean data).

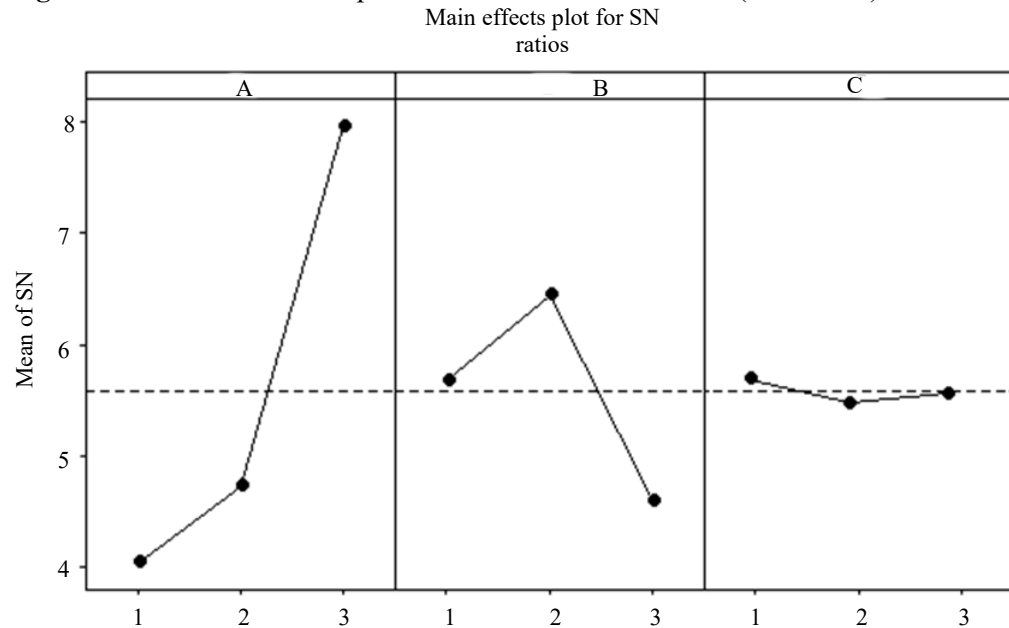


Figure 14. Effect of selected parameters on flexural modulus (S/N Data).

Table 11. ANOVA for flexural modulus.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	1.5922	1.5922	0.768	5.64	0.01
B	2	2.3916	2.3916	1.0693	8.06	0.002
C	2	0.3192	0.3192	0.2062	1.25	0.209
Error	20	2.6481	2.6481	0.1284		
Total	26	6.951				

Residual plots for flexural modulus

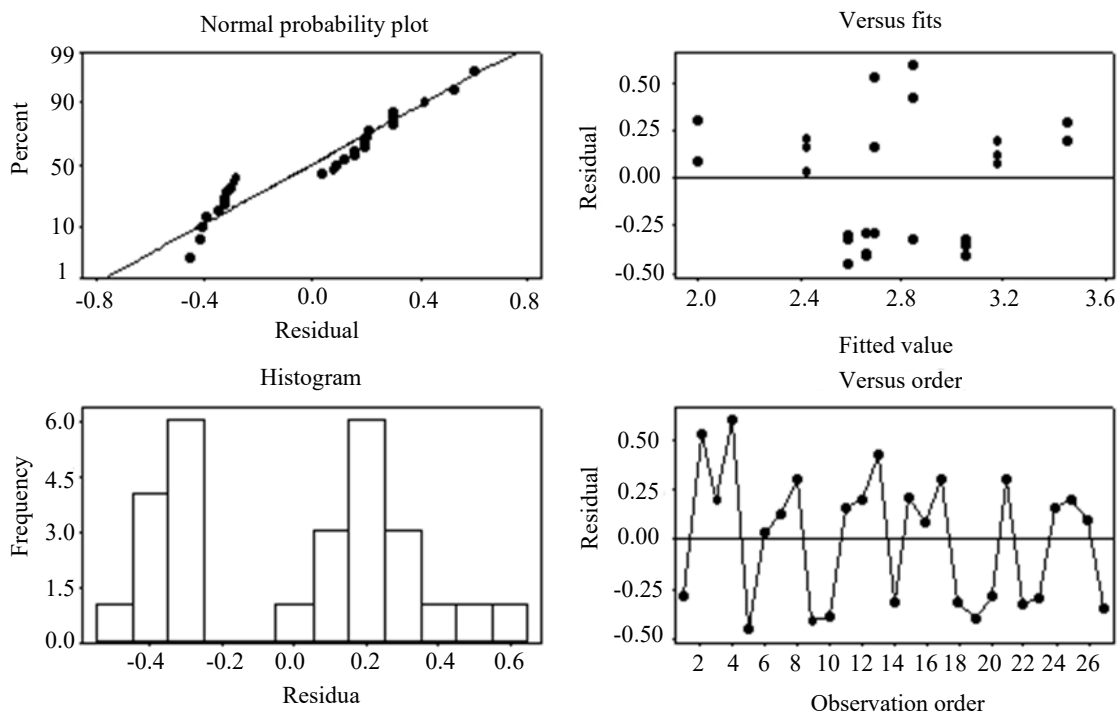


Figure 15. Effect of selected parameters on flexural modulus for developed composites (Residual)].

Table 12. Impact strength responses.

Exp.	A	B	C	Impact strength (J/m) (Response)			Average
				R_1	R_2	R_3	
1	1	1	1	8.23	8.07	8.20	8.17
2	1	2	2	8.86	9.10	8.92	8.96
3	1	3	3	6.48	6.32	7.11	6.64
4	2	1	2	8.07	8.38	8.19	8.21
5	2	2	3	10.45	9.67	9.82	9.98
6	2	3	1	6.85	6.52	7.04	6.80
7	3	1	3	9.07	9.16	9.82	9.35
8	3	2	1	10.19	9.87	10.08	10.05
9	3	3	2	8.07	7.38	7.11	7.52

Effect on Impact Strength

The experimental results for impact strength are presented in Table 12. Tables 13 and 14 list the rankings of the most influential parameters on the impact strength. The delta values and ranks shown in the last two rows of each table indicate the relative importance of each parameter in the response. The highest rank was B (fiber loading), followed by A (fiber type) takes second place. Therefore, the fiber weight percentage has a strong effect on the impact strength.

As shown in Figures 16 and 17, the highest impact strength was reached at the third level of fiber type (A3) JSH, the second level of fiber loading (B2) 12 wt.%, and the second level of injection pressure (C2) 50 Bar. The JSHHD composite exhibited the highest impact strength among the produced composites, although it was still less tough than 100% HDPE.

Table 15 shows that the most important parameter for impact strength is B, fiber loading, while A (fiber type) and C (injection pressure) are less important.

Table 13. Response of S/N ratio for impact strength.

Level	A	B	C
1	18.24	16.87	18.03
2	18.99	19.48	18.89
3	17.98	18.86	18.29
Delta	1.01	2.61	0.86
Rank	2	1	3

Table 14. Response of average for impact strength.

Level	A	B	C
1	8.27	6.98	8.05
2	8.97	9.42	8.94
3	7.98	8.81	8.23
Delta	0.99	2.44	0.89
Rank	2	1	3

Table 15. ANOVA for impact strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	5.990	5.990	2.930	2.88	0.058
B	2	29.255	29.255	14.563	14.34	0.003
C	2	4.135	4.135	2.003	1.97	0.136
Error	20	20.292	20.292	0.885		

Total	26	59.672
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Main effects plot for means
 Data means

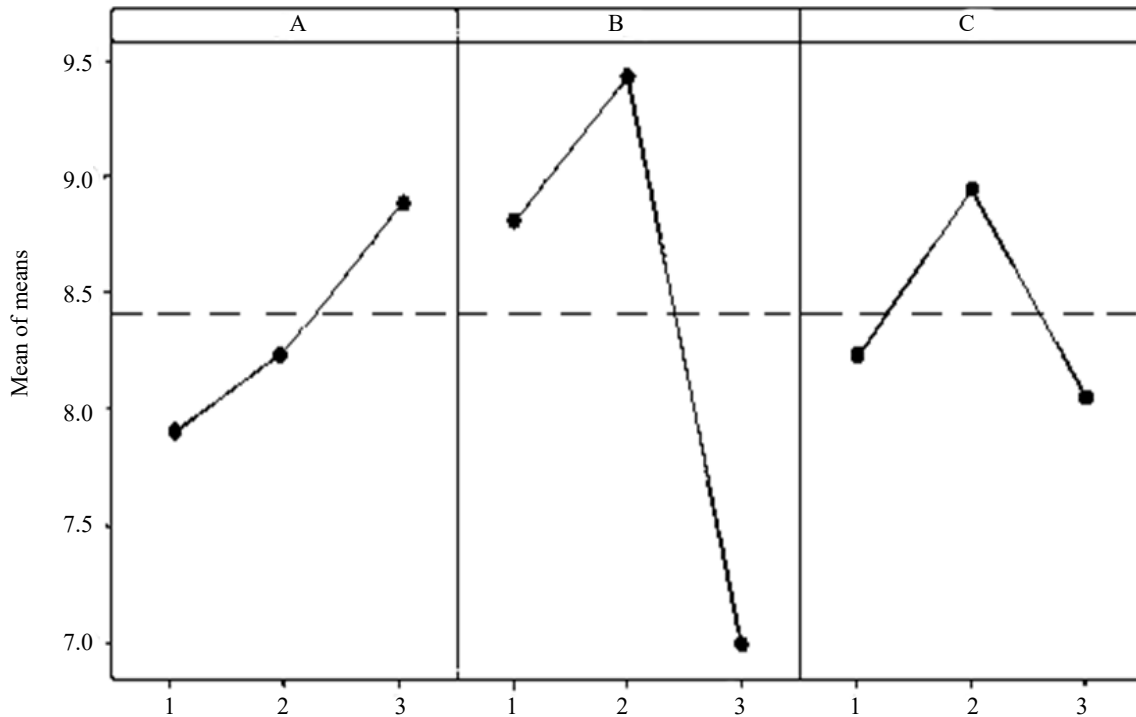


Figure 16. Developed composites' impact strength as a function of selected parameters (Mean data).

Main effects plot for SN ratios
 Data means

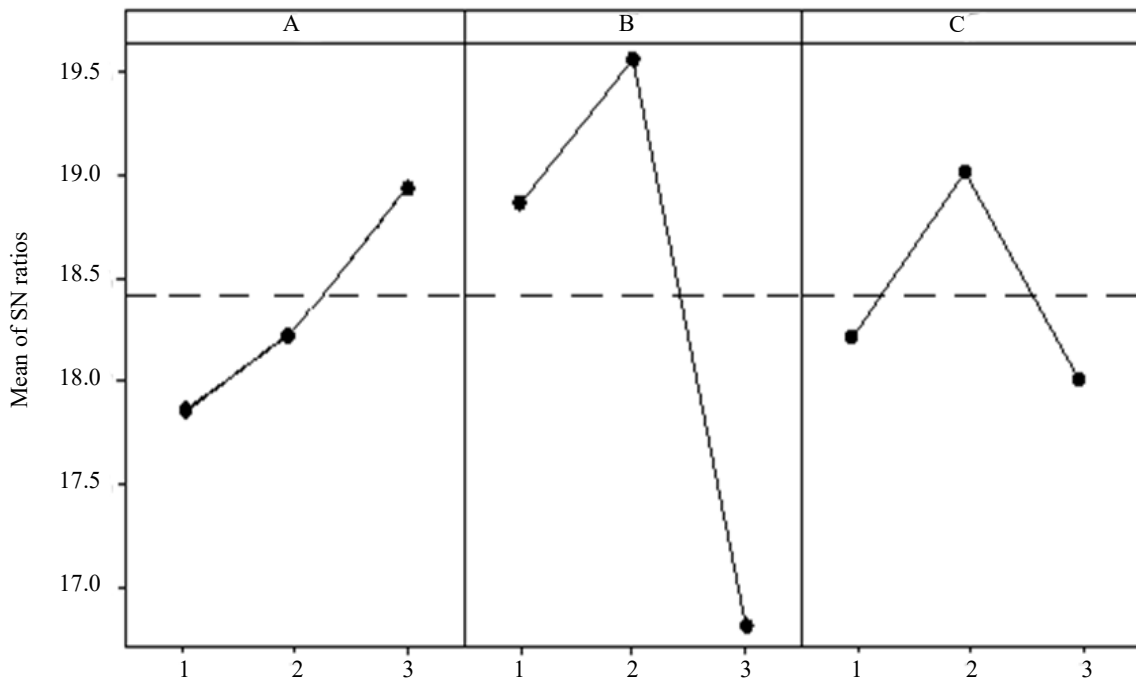


Figure 17. Impact strength for developed composites as a function of selected parameters (S/N Data).

The residual plot (Figure 18) for the impact strength shows that all residuals lie close to the straight

line in the normal probability plot; therefore, the data collection error is negligible.

Residual plots for impact strength

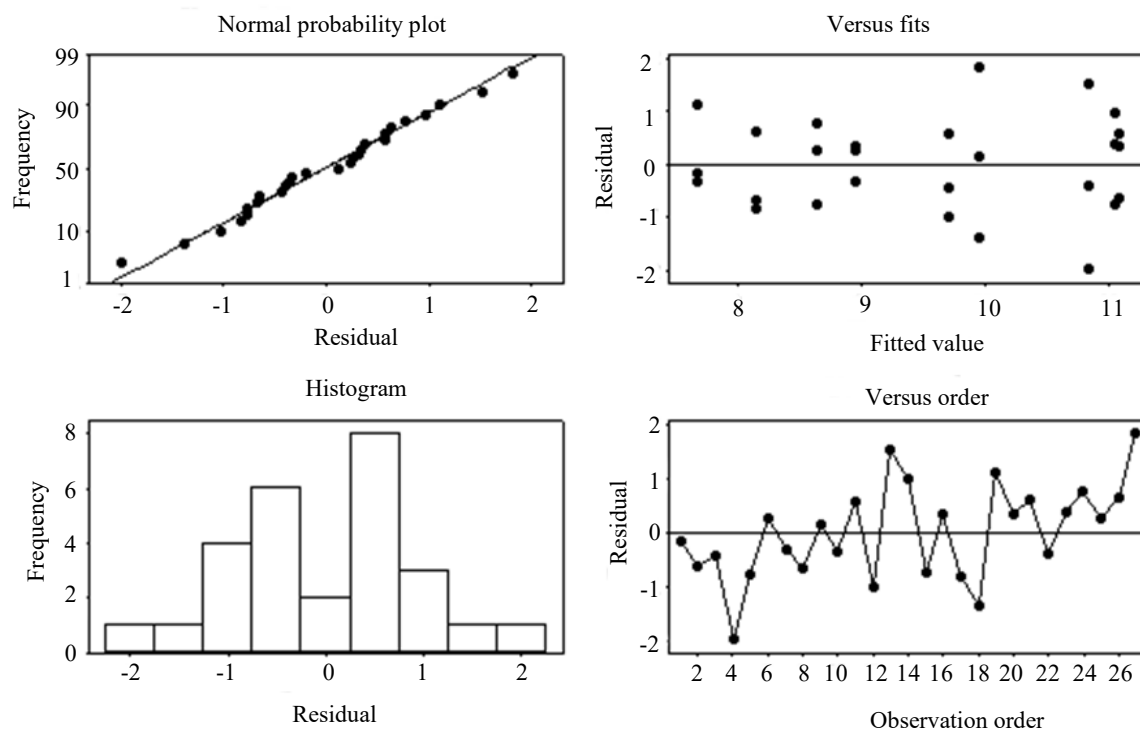


Figure 18. Impact strength of developed composites (residuals) in relation to specific parameters.

APPLICATIONS

The hybrid jute-sisal-hemp/HDPE composites developed in this study can be used in the following engineering and industrial sectors:

1. *Automotive industry*: Interior parts such as door panels, dashboard substrates, parcel shelves, and boot liners.
2. *Construction sector*: Non-structural building elements, such as wall cladding panels, partition boards, and modular flooring tiles.
3. *Furniture and consumer goods*: Chair shells, cabinet backs, storage boxes, and general household utility items.
4. *Packaging industry*: Rigid industrial crates, agricultural seedling trays, pallets, and protective shipping inserts.
5. *Electrical and electronics*: Low-voltage electrical enclosures, cable management trays, and outer casings for small domestic appliances.
6. *Sports and marine sector*: Protective gear shells, recreational equipment handles, and non-structural interior fittings for boats.
7. *Agriculture and horticulture*: Plant containers, grow trays, and crop storage bins, owing to the non-toxic and eco-friendly nature of the composite constituents.

DISCUSSION

The results obtained from the mechanical characterization and Taguchi-based process optimization of jute, sisal, and hemp fiber-reinforced HDPE hybrid composites form a coherent dataset that deserves further investigation. The sub-sections below cover the trends observed in flexural strength, flexural modulus, and impact strength, examine the role of fiber loading as the dominant process parameter, draw comparisons with related work, and offer broader thoughts on the practical value of the findings.

Interpretation of Flexural Strength and Flexural Modulus

1. *Progressive improvement with fiber loading*: The flexural strength and modulus of the hybrid composites increased steadily as the natural fiber content increased from 6 wt. % to 12 wt. %. There is a clear physical reason for this: at 12 wt. % fiber fraction, the reinforcing network becomes more interconnected, which allows the bending load to shift more efficiently from the relatively soft HDPE matrix to the stiffer natural fiber reinforcements. The fibers act as load-bearing elements and limit matrix deformation under bending, which directly increases both the peak stress at failure (flexural strength) and the initial slope of the stress-strain curve (flexural modulus).
2. *Role of chemical treatment in enhancing flexural response*: Part of the gain in flexural properties can also be linked to the NaOH surface treatment applied to the fibers before fabrication. Mercerisation removes surface impurities and wax layers, increases the surface roughness of the fiber, and helps create stronger mechanical interlocking at the fiber-matrix interface. A well-bonded interface allows stress to pass efficiently from the matrix to the fiber without early debonding, which is essential for obtaining good flexural performance from short fiber-reinforced thermoplastic composites.
3. *Influence of injection moulding on fiber orientation*: The injection moulding process naturally causes the preferential alignment of fibers along the melt flow direction. This flow-induced alignment tends to place a fair share of short fibers parallel to the principal stress axis during bending, adding to the gains observed in the flexural properties. The effect became more pronounced at higher fiber loadings, where a denser fiber population provided greater resistance to the bending deformation.
4. *Comparison with published literature*: The trend of increasing flexural strength and modulus with increasing natural fiber content in a thermoplastic matrix is well-established in the literature. Studies on short jute/polypropylene and sisal/polyethylene composites have also reported steady gains in bending stiffness as the fiber weight fraction increases, provided that the fiber dispersion remains uniform and the fiber-matrix bond is sufficiently strong through surface treatment. The findings of the present study are consistent with this established understanding in the natural fiber composite literature.

Interpretation of Impact Strength Behaviour

1. *Declining trend with increasing fiber content*: In contrast to the favorable response of the flexural properties, the impact strength of the hybrid composites decreased steadily as the natural fiber content increased. This inverse relationship is a well-known feature of short-fiber-reinforced thermoplastic systems and can be attributed to several mechanisms acting at the microstructural level.
2. *Stress concentration at fiber ends*: Owing to their geometry, short fibers bring a large number of fiber ends and fiber-matrix boundaries into the composite microstructure. These discontinuities act as local stress concentrators under dynamic and impact loading. As the fiber content increased, the number of stress concentration sites increased proportionally, facilitating cracks to initiate and reducing the energy required to propagate fracture through the material.
3. *Reduced matrix ductility*: HDPE is a semi-ductile polymer that can absorb a considerable impact energy through plastic deformation before fracture. Adding more natural fibers limits this plastic deformation in the matrix, because the fibers restrict the polymer chain movement around them. At higher fiber fractions, the composite shifted from a ductile failure mode to a more brittle one, with a corresponding drop in impact energy absorption.
4. *Fiber-matrix interface debonding under dynamic loading*: Under impact loading, the strain rates are significantly higher than those during quasi-static flexural testing. At these elevated rates, the fiber-matrix interface, even after alkali treatment, may not be strong enough to prevent rapid debonding. Once debonding starts, cracks travel quickly along the fiber-matrix boundaries, meeting little resistance and leading to lower measured impact energy values.
5. *Consistency with literature findings*: The drop in impact strength with increasing natural fiber loading in thermoplastic matrices has been reported in many comparable studies on jute, hemp, and sisal fibers in polyethylene and polypropylene matrices. This is seen as an inherent trade-off in short natural fiber composite design, where gains in stiffness and flexural resistance usually come at the cost of lower toughness and impact resistance. The present results agree with this

view and reinforce the need for interface engineering if both the flexural and impact properties are to be improved simultaneously.

However, this trade-off is considered acceptable in the context of targeted applications for such hybrid composites, on the processing side, there are several practical avenues worth exploring to bring the impact performance closer to that of neat HDPE. Adjusting the fiber length and controlling the fiber orientation during processing can significantly influence the energy absorption under sudden loads. Going beyond silane treatment to adopt more advanced fiber surface modification techniques may also help strengthen the interfacial zone and delay the crack initiation. Another viable approach involves introducing a toughening agent or rubber-based phase into the HDPE matrix, which is known to restore ductility without causing a significant drop in other mechanical properties.

Furthermore, revisiting the injection molding process parameters — particularly melt temperature and injection speed — holds practical promise. When these parameters are not well calibrated, internal voids tend to form within the composite, thereby weakening the structure under impact. Bringing these variables to their optimal settings could reduce such defects and improve the fiber–matrix contact, laying a stronger foundation for better impact behavior in subsequent investigations.

Fiber Loading as the Most Significant Control Parameter

1. *Taguchi and ANOVA findings:* The signal-to-noise (S/N) ratio analysis and ANOVA results both indicated to fiber loading (weight percentage) as the most influential control parameter for the mechanical behavior of the hybrid composites. It contributed the highest percentage to the total variation observed in both flexural and impact responses. This finding highlights the central role of reinforcement concentration in shaping the mechanical behavior of short fiber-reinforced thermoplastic systems.
2. *Why fiber loading dominates:* Fiber loading directly controls the volume fraction of the load-bearing phase in the composite. Even small changes in the fiber weight percentage cause measurable shifts in the effective stiffness, strength, and toughness of the composite. Fiber type does bring in differences linked to the intrinsic properties of each fiber (density, modulus, and surface chemistry), and injection pressure affects fiber dispersion and void content, but neither has as strong and consistent an effect across all three measured responses as the fiber weight fraction.
3. *Practical implication of this finding:* From a process engineering perspective, the fact that fiber loading is the dominant parameter means that adjusting the reinforcement content is the most effective lever a composite manufacturer has for shaping the mechanical profile of jute-hemp-sisal/HDPE hybrid composites. Where high flexural rigidity is required, a higher fiber fraction (approximately 18 wt. %) is the right choice, while for applications where impact resistance matters more, a lower fiber loading (around 6 wt.%) is more suitable so that matrix toughness is preserved.

Comparative Behaviour of Jute, Sisal and Hemp Fibers

1. *Inherent property differences:* Although fiber loading came out was the main governing parameter, the choice of natural fiber also influenced the extent to which the mechanical properties changed. Jute and hemp fibers, with their relatively higher cellulose content and tensile modulus, generally contribute more to the gains in flexural stiffness. While Sisal offers reasonable mechanical properties, it has a somewhat lower cellulose content and higher elongation at break than jute and hemp, which may explain the differences observed in its reinforcing efficiency within the HDPE matrix.
2. *Hybrid reinforcement advantage:* Using three different natural fibers within a single HDPE matrix introduces a hybrid reinforcement effect, where combining two or more fiber types can provide composite properties that go beyond what any single fiber can achieve. The complementary mechanical traits of jute, hemp, and sisal, when spread evenly through the HDPE matrix, can lead to a more balanced stress distribution under loading, particularly in bending.

Role of Injection Pressure in Composite Processing

1. *Influence on material flow and fiber dispersion:* Injection pressure controls the speed and completeness of filling the mould cavity with polymer fiber melt. At lower pressures (40 Bar), there is a risk of incomplete cavity filling, less uniform fiber dispersion, and the formation of micro-voids, all of which can affect the mechanical properties. At higher pressures (60 Bar), the better melt flow leads to a more uniform fiber distribution and more complete cavity filling, which usually supports better mechanical performance.
2. *Pressure-induced fiber damage:* On the other hand, very high injection pressures can grind down natural fibers as they pass through the barrel and gate, lowering their effective length and aspect ratio. Because the reinforcing efficiency of short fibers depends directly on the aspect ratio, this pressure-induced shortening can cancel out part of the benefit gained from better dispersion at higher pressures. This competing effect helps explain why the injection pressure, although still significant, contributes less to the overall mechanical variation than fiber loading.

Broader Insights and Engineering Significance

1. *Viability of injection moulding for natural fiber composites:* The results of this study confirm that injection moulding is a viable and industrially scalable route for manufacturing natural fiber-reinforced HDPE hybrid composites with reproducible mechanical properties. This process provides precise control over the fiber content, pressure, and temperature, making it well suited for the mass production of composite parts with defined performance targets.
2. *Trade-off between stiffness and toughness:* One key insight from this study is the inherent mechanical trade-off between stiffness and flexural strength on the one hand and impact toughness on the other in short natural fiber-reinforced thermoplastics. This trade-off is not unique to the present material system but is a widely recognized challenge in composite design. Addressing this issue will likely require chemical or physical modifications of the fiber-matrix interface, the use of impact modifiers or toughening agents, or the transition from short fibers to continuous or woven fiber architectures.
3. *Environmental and sustainability perspective:* Beyond mechanical performance, these hybrid composites offer clear environmental advantages over conventional glass or carbon fiber-reinforced synthetic composites. Natural fibers are renewable, biodegradable, carbon-neutral in production, and noticeably lighter in density. The fact that these composites can be processed using standard industrial injection- moulding equipment further strengthens the case for their adoption in environmentally sensitive sectors, such as automotive interiors, consumer goods, and low-load structural components.
4. *Alignment with sustainable manufacturing goals:* The growing industrial and regulatory push for sustainable materials and green manufacturing makes the development of optimized natural fiber composite systems especially timely. The findings of this study add experimental evidence that supports the wider goal of replacing petroleum-based synthetic composites with renewable, eco-friendly alternatives without losing significant structural performance, provided that the processing parameters, particularly fiber loading, are carefully controlled.

Overall, the results and interpretation in this section show that the mechanical behavior of jute-hemp-sisal/HDPE hybrid composites made through injection moulding is shaped by a complex interplay of fiber type, fiber concentration, and processing conditions. Fiber loading was the most influential variable, and careful tuning using the Taguchi method allowed the composite properties to be tailored to specific end-use requirements. These findings provide a solid basis for the conclusions drawn in the following section.

CONCLUSION

Based on the experimental work and analysis of jute, hemp, and sisal fiber-reinforced HDPE hybrid composites made through injection moulding, the following conclusions were drawn:

1. *Successful fabrication*: Injection moulding was an effective and reliable method for producing short natural fiber-reinforced HDPE hybrid composites, with consistent specimen quality across all experimental runs.
2. *Flexural properties*: Both flexural strength and modulus increased steadily as the natural fiber loading increased from 6 wt. % to 12 wt. %, confirming that natural fibers work well as stiffness-enhancing reinforcements in the HDPE matrix.
3. *Impact strength*: Impact strength decreased consistently as the fiber content increased, owing to the greater stress concentration at the fiber ends, restricted matrix ductility, and a shift towards more brittle fracture behavior at higher fiber fractions.
4. *Dominant process parameter*: Fiber loading (weight percentage) was identified as the most influential control parameter by both the Taguchi S/N ratio analysis and ANOVA, contributing the largest share to the variation in all the mechanical responses measured.
5. *Taguchi and ANOVA effectiveness*: The L9 orthogonal array efficiently optimized the three process parameters in nine runs, while ANOVA quantified the relative contribution of each, confirming fiber loading as the primary factor and fiber type and injection pressure as secondary factors.
6. *Hybrid reinforcement*: Using jute, hemp, and sisal fibers together in a single HDPE matrix confirmed that the hybrid reinforcement strategy is workable, providing a fairly balanced mechanical profile across all composite formulations.
7. *Sustainability*: The combination of renewable natural fibers with a recyclable thermoplastic matrix renders these composites a sustainable, eco-friendly alternative to conventional synthetic fiber-reinforced polymers for low-to-medium load engineering applications.

In summary, fiber loading is a critical design variable and selecting it carefully using the Taguchi method allows the mechanical behavior of hybrid natural fiber/HDPE composites to be tailored for specific engineering end-uses.

Future Scope

Although this study lays a useful foundation for understanding the mechanical behavior of jute-hemp-sisal reinforced HDPE hybrid composites made through injection moulding, several research directions remain open. The points below outline possible areas for future work across different fields;

Materials Science and Fiber Research

1. *Exploration of alternative natural fibers*: Future work could incorporate other lignocellulosic fibers, such as coir, bamboo, kenaf, banana, and flax, into the HDPE matrix. A side-by-side comparison of these fibers with jute, hemp, and sisal would help identify the best reinforcement for specific mechanical applications.
2. *Effect of fiber geometry and orientation*: The effect of fiber aspect ratio, length distribution, and preferential orientation on composite stiffness and fracture behavior was not addressed in this study. Varying these parameters systematically during injection moulding could yield composites with more predictable and directional properties.
3. *Hybrid stacking sequences*: Investigating alternating and layered hybrid fiber arrangements as opposed to uniform blends may uncover synergistic interactions between fiber types, further enhancing the balance between flexural and impact performance.

Surface Treatment and Interface Engineering

1. *Chemical surface modifications*: The drop in impact strength may be partly due to weak fiber-matrix interfacial bonding. Future studies should consider alkali treatment (mercerisation), silane coupling, acetylation, benzoylation, and maleic anhydride grafting to strengthen the adhesion between hydrophilic natural fibers and the hydrophobic HDPE matrix.

2. *Physical and biological treatment methods*: Beyond chemical routes, physical surface treatments such as plasma treatment, gamma irradiation, and corona discharge, as well as biological methods using enzymes or fungi, could be tested for how well they alter fiber surface topography and improve compatibility at the interface.

Manufacturing and Process Engineering

1. *Advanced multi-objective process optimization*: While Taguchi and ANOVA were used here, future work could turn to more advanced optimization strategies, such as Response Surface Methodology (RSM), Grey Relational Analysis (GRA), or machine learning approaches, such as Artificial Neural Networks (ANN) to optimize several mechanical responses simultaneously.
2. *Comparative fabrication techniques*: A side-by-side study of alternative processes, such as compression moulding, extrusion compounding, and resin transfer moulding, alongside the injection moulding used here, would shed light on how the processing route affects the microstructure, fiber degradation, and final mechanical properties.
3. *Effect of recycling and reprocessing*: Because HDPE is a thermoplastic, the hybrid composites in this study can be reprocessed. Future work should examine how mechanical properties hold up across multiple reprocessing cycles, which is key information for placing these materials in a circular economy context.

Mechanical and Structural Characterization

1. *Extended mechanical testing*: Future work should broaden the mechanical characterization to cover tensile strength, compressive strength, hardness (Shore D and Rockwell), fatigue life, and creep behavior. This would provide a fuller picture of the composite performance and suitability for structural or semi-structural roles.
2. *Microstructural and fractographic analysis*: Scanning electron microscopy (SEM) of fracture surfaces, along with X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR), can provide deeper insight into failure mechanisms, fiber-matrix interaction, and degree of crystallinity, all of which can directly guide improvements in composite design.

Thermal and Physical Properties

1. *Thermal characterisation*: Thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and dynamic mechanical analysis (DMA) should be carried out to learn more about the thermal stability, glass transition behavior, and viscoelastic response of the hybrid composites. These properties are important for applications involving elevated service temperatures.
2. *Water absorption and moisture resistance*: Natural fiber composites tend to absorb moisture, which can degrade their mechanical properties over time. Future work should measure the water absorption kinetics of these hybrid composites and consider matrix modifications or fiber treatments that can reduce hygroscopic behavior during long exposure.

Nanotechnology and Advanced Reinforcement

1. *Nano-filler incorporation*: Adding nano-reinforcements such as nanoclay, graphene oxide, carbon nanotubes, and nano-silica alongside the existing natural fibers could bring multifunctional gains, including better stiffness, barrier resistance, and thermal conductivity. Future work should examine how these nano-fillers disperse within the HDPE matrix during injection moulding and how they affect the composite microstructure.
2. *Cellulose nanocrystals (CNCs) as reinforcement*: Cellulose nanocrystals obtained from jute, hemp, or sisal can be isolated and used as a secondary nano-scale reinforcement within the same composite system. Their high aspect ratio and exceptional specific stiffness make them strong candidates for boosting both the modulus and interfacial interactions at the nanoscale.

Sustainability and Environmental Assessment

1. *Life cycle assessment (LCA)*: A full LCA study comparing the environmental impact of jute-hemp-sisal/HDPE hybrid composites with traditional glass fiber-reinforced polymer composites would provide quantitative evidence of the ecological benefits offered by natural fiber alternatives and support their use in environmentally sensitive industries.

Industrial and Structural Applications

1. *Automotive and transportation sector*: owing to their low density, acceptable flexural properties, and sustainable sourcing, the hybrid composites developed in this study are promising for automotive interior parts, such as door panels, dashboard sub-structures, and trunk liners. Future studies should evaluate these composites against industry-specific performance benchmarks and crash safety standards.
2. *Construction and civil engineering*: The use of HDPE-based natural fiber composites in low-load structural elements, cladding panels, flooring systems, and modular furniture in the construction sector deserves dedicated study. Prototype-scale testing under real-world loading and environmental conditions is a logical step towards moving laboratory findings into practical engineering applications.

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