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Fabrication and Characterization of Hybrid Composites Using Natural Fibers Reinforced in HDPE and Optimization of Injection Moulding Process Parameters to Minimize Shrinkage

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Abstract

Materials are crucial for advancing human living standards. Over the past 20 years, composite materials have garnered significant attention owing to their unique properties and applications across various sectors. This study outlines the creation and analysis of a novel series of natural fiber-based composites, which incorporate jute, sisal, and hemp as reinforcements, with high-density polyethylene (HDPE) serving as the matrix, and produced through injection moulding. This study examines the effects of different natural fiber contents on the tensile strength, tensile modulus, and Shore-D hardness of hybrid composites, and identifies optimal injection moulding parameters to minimize shrinkage defects. It was evaluated that incorporating three different fibers into HDPE led to a decrease in tensile strength, which had a similar effect, showing a decline in tensile modulus, but an increase in hardness. The findings indicate that a melting temperature of: - 190°C, refilling pressure of: - 85 MPa, and cooling time of: - 11 sec resulted in the least shrinkage. In the final part of the study, the best parameters in terms of the mean and signal-to-noise ratios, responses, and characteristics were determined by analyzing the response plots and variance tables. Consequently, the results of this study are interdisciplinary and may interest mechanical engineers and material scientists in the automotive industry, government bodies, and the development of small-scale eco-friendly industries aiming to achieve an effective method for processing natural fiber-reinforced hybrid composites with desired properties to produce environmentally friendly composite materials.

Keywords: Hybrid composite, tensile strength, tensile modulus, hardness, HDPE

INTRODUCTION

Natural-fiber-reinforced hybrid composites have gained increasing interest owing to their environmental, economic, and mechanical advantages. Their low cost, abundance, and favorable strength-to-weight ratios render them suitable reinforcements for construction, packaging, furnishing, and automotive applications [1]. In recent years, research on the replacement of man-made fibers with natural fibers as reinforcement in plastic composites has increased dramatically, and researchers are continuously making efforts to invent new hybrid materials to fulfill the increasing requirements of the automotive, aerospace, household, food packaging, and other industries [2]. However, despite such advances in hybridization, there are still many challenges in the development of natural-fiber-based hybrid composites.

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In the past years, most of the work reported has used only a single type of natural fiber as reinforcement in a polymer matrix for fabricating composites. Researchers have been curious about enhancing the mechanical properties of single-fiber-reinforced polymer composites by reinforcing two types of natural fibers in the same matrix (*i.e., hybridization*) [3]. With hybridization, we obtained a balance between cost and performance, which cannot be achieved by single-fiber reinforcement. The positive effects of hybridization, *that is,* by reinforcing two different types of fibers in a single matrix, have already been noticed by various researchers. Junior et al. [4] observed an improvement in the tensile strength of a polyester matrix composite hybridized with ramie and cotton fibers. Idicula et al. [5] reported improved mechanical properties in hybrid natural fiber composites, including banana/sisal-polyester and kenaf/wood flour-polypropylene systems. Building on these findings, the present study investigated the mechanical behavior of a tri-hybrid composite reinforced with jute, sisal, and hemp fibers within a common matrix. Despite extensive research on polypropylene-based composites, studies on natural- fiber-reinforced HDPE remain limited, warranting a dedicated investigation into their mechanical behavior.

Among the various fabrication techniques, injection moulding is widely preferred for natural fiber-reinforced composites because of its fast cycle times, dimensional accuracy, and large-scale production capabilities [6, 7]. However, the influence of injection moulding parameters on jute, sisal, and hemp fiber-reinforced HDPE hybrid composites has not been sufficiently explored in the literature.

In injection-moulding machine fabrication, shrinkage is one of the most important reasons that cause dimensional changes in the part, and it can be minimized by setting optimal process parameters on the injection-moulding machine Pervez et al. [8].

This study develops a hybrid HDPE composite, reinforced with three natural fibers via injection moulding, analyzing how fiber type, fiber percentage and injection pressure affect mechanical properties, while optimizing parameters to minimize shrinkage defects.

LITERATURE REVIEW

Altan et al. (2010) [9] demonstrated that the injection moulding cycle time for DVD manufacturing can be reduced by optimizing the mould travel distance, speed, cooling time, and hold time. Huang and Tai (2001) [10] studied the effect of five input parameters on surface quality of thin moulded parts. The input parameters were the mould temperature, melting temperature, packing pressure, packing time, and injection time. Oktem et al. (2007) [11] applied the Taguchi method to optimize injection moulding parameters, evaluating shrinkage alongside weight, weld lines, and sink marks. This approach achieved multi-characteristic quality optimization with minimal experimental runs, offering significant cost savings. Abdul et al. (2020) [12] in their paper determined optimal injection moulding condition for minimum shrinkage by the DOE technique of Taguchi methods. Packing pressure was found to be the most effective factor for polypropylene (PP), followed by packing time, injection pressure, and melt temperature. Dhakal (2007) [13] reported that the mechanical properties of hybrid composites depend on the fiber type and orientation. It was observed that carbon with hemp yielded better results than carbon and jute because hemp has better tensile strength than jute. Gbenga Ekundayo, Sam Adejuyigbe (2019) [14] 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. P. Yadav. (2021) [15] noted that natural fiber-reinforced polymer composites reduce dependence on non-renewable resources while offering significant energy and environmental benefits. Bio-nanocomposites also show promise in food packaging through enhanced barrier and antimicrobial properties. Zakka WP (2021) [16] the choice of matrix significantly influences mechanical assessments. Typically, two main types of polymers are utilized: thermoplastics and thermosets. Haris NIN (2022) [17] Plant fibers have attracted attention as reinforcements for polymer matrices, and research has mainly focused on their thermomechanical performance. Plant fibers can enhances the mechanical characteristics of biocomposites with thermoplastic matrices. Chai, B. X., B. Eisenbart (2023) [18] the increasing depletion of limited resources is prompting researchers to explore alternative ways of manufacturing biomass. One trend is the gradual technical replacement of high-performance materials with more economical or valuable products. Ghernaout (2024) [19] demonstrated the promising potential of YF/HDPE biocomposites as sustainable and cost-effective replacements for conventional materials in diverse applications. Indeed, given their load-bearing capacity and recyclability, this type of biocomposite is a wise choice for manufacturing automotive interior trim, sporting goods, and eco-friendly building materials. Dezfooli et al. (2024) [20] 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) [21] optimized the injection moulding parameters for an LCD monitor rear cover using the Taguchi method combined with PSO, achieving regression and warpage errors below 2.5% and 3.5%, respectively. Aslam et al. (2025) [22] used the Taguchi L27 orthogonal array to improve PET preform moulding in industry, achieving a 4.75% drop in warpage and a 2.05% reduction in weight. These studies confirm that the Taguchi-based DOE, especially when paired with verification tests or hybrid approaches, lowers moulding defects and increases product quality. Abdulrahman et al. (2025) [23] 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, indicating the value of Taguchi methods for processing biopolymer composites. Palanisamy and Kalimuthu (2022) [24] Sliding wear tests run up to 30 N load and 75 m distance showed that the 40 wt% samples held up best — wear damage was more contained. What made the results particularly useful was the post-moisture data: after full water saturation, tensile and flexural strengths dropped by less than 10%, which is a reassuring margin for real service conditions. Aruchamy et al. (2025) [25] fabricated composites from Palmyra Palm Leaflet (PPL) and Coconut Sheath Leaf (CSL) fibers, blending in tamarind shell powder as a natural filler. Among the combinations tried, the 20% PPL / 10% CSL mix came out on top — tensile strength reached 42.22 MPa, flexural strength 94.35 MPa, and the interlaminar shear strength (ILSS) was measured at 7.52 MPa. The study makes a practical point: even modest adjustments to fiber ratio can shift the mechanical response noticeably, which has direct implications for composite design in thermoplastic systems. Ayrilmis et al. (2025) [26] explored what happens when recycled polypropylene is filled with crushed manhole cover material (CMC) and MDF sawdust — both low-cost industrial waste streams. Maleic anhydride grafted PP was used to compatibilize the blend. Loading the filler up to 40 wt% (split equally between CMC and MDF) pushed bending strength to 46.4 MPa and flexural modulus to 3399 MPa. The progressive stiffening trend with filler addition is consistent with behaviour seen in HDPE-based systems and supports the rationale for using thermoplastic matrices in hybrid fiber composite fabrication. Ramasubbu et al. (2024) [27] who reinforced epoxy with Areca catechu fibers (ACF) and added silicon carbide (SiC) as a secondary filler. ACF carries a high cellulose fraction of 63.2 wt%, which partly explains its mechanical potential. Tensile and flexural performance improved as total filler content rose from 40 to 50 wt%, but fell off beyond that point. The SiC particles showed a dual behaviour: they weakened bending and flexural response at 40–50 wt% yet improved both at 60 wt%. This non-linear response flags the need for careful filler dosing — something directly relevant when setting injection molding parameters for hybrid HDPE composites.

Palanisamy et al. (2024) [28] reviewed the environmental case for natural fiber composites, covering fibers such as jute, coir, sisal, flax, hemp, banana, and PALF. The key argument is straightforward: these fibers are renewable, biodegradable, and lightweight, with specific tensile and flexural properties that can match or approach glass fiber performance in many structural applications. Challenges around moisture uptake and fiber-matrix bonding are acknowledged, but the authors frame them as solvable engineering problems rather than fundamental barriers. This environmental justification is central to the present work, which deliberately selects three natural fibers for reinforcement in an HDPE matrix.

After reviewing the existing literature on natural fiber-reinforced composites, it was observed that the use of natural fibers alone in a polymer matrix is inadequate for satisfactorily addressing all the technical requirements of a fiber-reinforced composite. Therefore, hybridizing natural fibers with a polymer matrix can significantly improve the strength and stiffness of natural fiber-reinforced composites.

Although extensive literature exists on natural fiber-reinforced polypropylene composites, studies on tri-hybrid natural fiber-reinforced HDPE remain limited, particularly regarding mechanical characterization and the optimization of injection moulding parameters. This study addresses this gap by investigating the mechanical behavior and process optimization of jute, sisal, and hemp fiber-reinforced high-density polyethylene (HDPE) hybrid composites.

Therefore, in this study, the mechanical properties, tensile strength, tensile modulus, and hardness of Jute, Sisal and Hemp fiber-reinforced high-density polyethylene (HDPE) composites fabricated using the injection moulding technique were investigated. The effects of varying amounts of fibers injected at different injection pressures on the mechanical properties were tested and analyzed. The optimal injection moulding process parameters were determined to reduce the shrinkage defect by designing an experiment using the taguchi method.

RESEARCH METHODOLOGY

Overall Research Design

The experimental work described in this section was structured around three overarching objectives.

1. The first objective was to fabricate hybrid composites by incorporating three different natural cellulosic fibers, namely jute, hemp, and sisal, into a High-Density Polyethylene (HDPE) matrix through injection moulding.
2. Second, we analyzed how changing parameters, such as the fiber type, weight proportion, and injection pressure, affect the tensile strength, tensile modulus, and surface hardness. The best parameters were determine using ANOVA and the Signal-to-Noise Ratio (SNR).
3. The third objective was to determine the combination of injection moulding settings that minimizes the dimensional shrinkage in the fabricated composite.

Work Flowchart

The entire experimental work is framed in the flowchart shown in Figure 1.

Materials

Matrix and Reinforcement

High-Density Polyethylene was chosen as the matrix material for this study. Among commodity thermoplastics, HDPE offers a useful combination of moderate stiffness, reasonable impact resistance, and very low moisture absorption, which makes it suitable as a host material for natural fiber reinforcement.

Jute, hemp, and sisal were selected as the reinforcing fibers. All are plant-derived, cellulose-rich bast or leaf fibers that are readily available at a modest cost. Jute is one of the most commonly used natural fibers in polymer composites and contributes to useful axial stiffness. Hemp has a comparatively high cellulose content of approximately 70–74%, which translates into good specific stiffness and strength. Sisal, a leaf fiber, has a higher elongation at failure than the other two and has been reported to bond well with thermoplastic matrixes. When used in combination, the three fibers were expected to produce a hybrid system whose response reflected the distinct contributions of each constituent. In this study, jute, sisal, and hemp fibers were used as reinforcements, and HDPE was used as a matrix to fabricate hybrid composites. The fibers were purchased from Chandra Prakash & Company, Jaipur, Rajasthan, India, and HDPE was purchased from Batra Polymers, Ludhiana, Punjab, India. Hybrid composite was fabricated by injection moulding technique.

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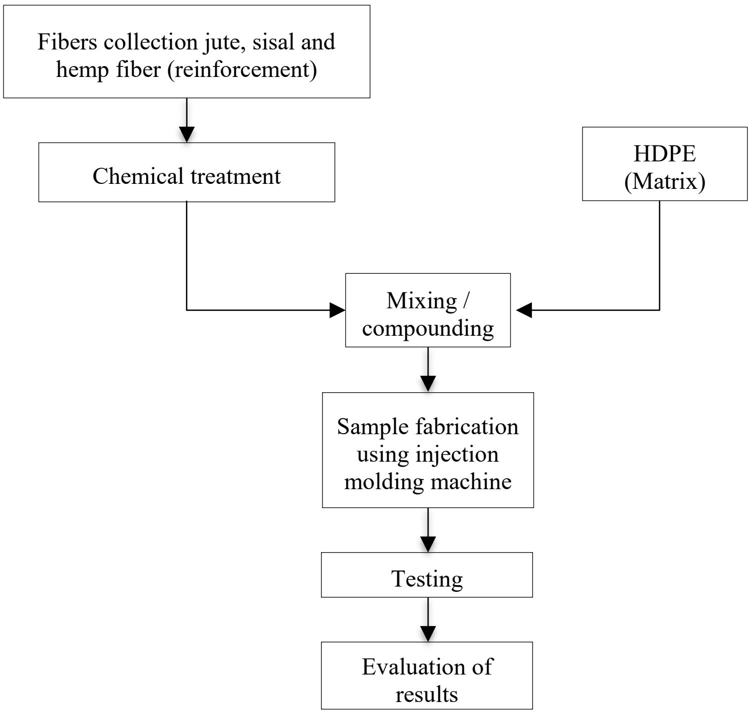

Figure 1. Experimental work flowchart.

Surface Treatment of Fibers

Natural fibers are inherently hydrophilic because their cell walls are rich in hydroxyl groups, whereas HDPE is nonpolar and hydrophobic. Without surface modification, this chemical mismatch leads to weak interfacial bonding, which limits the load transfer efficiency of the composite. To address this issue, all three fibers were subjected to alkali treatments before processing.

Alkaline Treatment of Fibers

The chemical framework and surface bonding of fibers are important parameters for the fabrication of natural fiber-based composites. A high degree of surface bonding between the dispersoid and matrix material is preferable for better properties, such as tensile, flexural, hardness, and impact properties of the composite. Therefore, many researchers [29-32] have conducted research on the treatment of fibers to increase their bonding with the matrix. The mechanical properties of the developed composites can be enhanced by the amount of the individual constituent and its properties and by the nature of the interfacial region between the matrix material and reinforcement. Natural fiber composites are not very important because of their poor interfacial adhesion. Generally, the interfacial properties between the fiber and matrix are low because of the hydrophilic nature of natural fibers. Therefore, chemical modifications are necessary to improve the fiber interface [33]

Jute (J), sisal (S), and hemp (H) fibers were treated with sodium hydroxide (NaOH) solution. NaOH in pellet form was obtained from Maya Chemtech India Private Limited, New Delhi. NaOH pellets (900 g) were placed in 15 liters water in a bucket. NaOH pellets are soluble in water, and a 6% NaOH solution was prepared. These three short fibers were separately immersed in the NaOH solution for 24 h at room temperature [34]. Subsequently, the treated fibers were washed separately with distilled water several times to remove excess NaOH until a pH value of 7 was reached. Finally, these short fibers were separately kept in trays homogeneously for drying in a hot air oven at 90º C for 24 h until a constant mass was reached, and then stored in sealed bags to prevent reabsorption of moisture before use.

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.

Taguchi Method

The Taguchi technique is a simple yet efficient methodology used to evaluate and improve products, processes, materials, and equipment by studying key controlling variables and optimizing designs to achieve optimal results. It aims to enhance the desired characteristics while simultaneously reducing the defects. This method is broadly applicable across the engineering, manufacturing, computer-aided design, banking, and service industries. Notably, it significantly reduces the cost and time associated with experimental research, making it highly valuable when achieving research objectives with the fewest number of experiments is essential. In this regard, the Taguchi technique provides an efficient and systematic approach for the test procedure to determine the optimum settings of selected parameters for the best performance and cost, and to save considerable time. In this method, Based on the experimental conditions, the constructed table was chosen as an orthogonal array, as shown in Table 1. A large number of test procedures are required when the number of selected parameters is increased. The Taguchi technique can easily solve this problem using an orthogonal array.

Table 1. Orthogonal arrays selector.

LEVELS	1	2	3	4	5	6	7	8	9	10	11	12
	2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27
	4	L16	L16	L16	L16	L32	L32	L32	L32	L32		
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50

Table 2. Design Parameters and Their Levels.

Number of parameters	Selected parameters	Levels			Unit
		1	***2***	***3***	
1	Fiber type	J	JH	JSH	-
2	Fiber loading	6	12	18	Wt. %
3	Injection pressure	40	50	60	Bar

Fabrication of Composites

The fabrication was performed in accordance with the conditions listed in Table 2. Three parameters were considered as selected parameters. These are Fiber type, fiber loading, and Injection Pressure. Each parameter has three levels: J (Jute), JH (Jute and Hemp), and JSH (Jute, Sisal, and Hemp; 6, 12, 18, and 40, 50, 60, respectively). Therefore, an L_9 orthogonal array was used to conduct the experiments. The fabrication was conducted as per the experimental design (number of parameters and their levels are given in Table 3), which was designed as per orthogonal array L_9 for data collection. We considered the collection of data by means of 9 conditions. Each condition will be determined by factors, for instance, the first condition is identified by fiber type and fiber loading by weight percentage (wt. %) and Injection Pressure (Bar). Therefore, the orthogonal array was selected with $L_9\,(3^3)$, which provided the order of experiments, as presented in Table 4. All experimental results were transformed into Taguchi analysis using MINITAB software version 18.

Table 3. Taguchi L_9 orthogonal arrays.

Experiment number	Fiber type A	Fiber loading B	Injection pressure C
1.	Fiber 1	Fiber loading 1	Injection pressure 1
2.	Fiber 1	Fiber loading 2	Injection Pressure 2
3.	Fiber 1	Fiber loading 3	Injection Pressure 3
4.	Fiber 2	Fiber loading 1	Injection Pressure 2
5.	Fiber 2	Fiber loading 2	Injection Pressure 3
6.	Fiber 2	Fiber loading 3	Injection Pressure 1
7.	Fiber 3	Fiber loading 1	Injection Pressure 3
8.	Fiber 3	Fiber loading 2	Injection Pressure 1
9.	Fiber 3	Fiber loading 3	Injection Pressure 2

Table 4. Experimental layout based on L_9 orthogonal arrays.

Exp. no.	Selected parameters levels		
	Fiber type	***Fiber loading***	***Injection pressure***
	A	*B*	*C*
R_1	J (Level 1)	6 (Level 1)	40 (Level 1)
R_2	J (Level 1)	12 (Level 2)	50 (Level 2)
R_3	J (Level 1)	18 (Level 3)	60 (Level 3)
R_4	JH (Level 2)	6 (Level 1)	50 (Level 2)
R_5	JH (Level 2)	12 (Level 2)	60 (Level 3)
R_6	JH (Level 2)	18 (Level 3)	40 (Level 1)
R_7	JSH (Level 3)	6 (Level 1)	60 (Level 3)
R_8	JSH (Level 3)	12 (Level 2)	40 (Level 1)
R_9	JSH (Level 3)	18 (Level 3)	50 (Level 2)

Table 5. Process parameters and levels for shrinkage.

Number of parameters	Selected parameters	Levels			Unit
		1	2	3	
1	Melting temperature, A	180	190	200	°C
2	Refilling pressure, B	65	75	85	MPa
3	Cooling time, C	5	8	11	Sec

Table 6. L9 orthogonal array for shrinkage.

Exp. No.	Selected parameters levels			Parameters setting
	Melting temp	*Refilling pressure*	*Cooling time*	
	A	*B*	*C*	
R_1	180 (Level 1)	65 (Level 1)	5 (Level 1)	A1B1C1
R_2	180 (Level 1)	75 (Level 2)	8 (Level 2)	A1B2C2
R_3	180 (Level 1)	85 (Level 3)	11 (Level 3)	A1B3C3
R_4	190 (Level 2)	65 (Level 1)	8 (Level 2)	A2B1C2
R_5	190 (Level 2)	75 (Level 2)	11 (Level 3)	A2B2C3
R_6	190 (Level 2)	85 (Level 3)	5 (Level 1)	A2B3C1
R_7	200 (Level 3)	65 (Level 1)	11 (Level 3)	A3B1C3
R_8	200 (Level 3)	75 (Level 2)	5 (Level 1)	A3B2C1
R_9	200 (Level 3)	85 (Level 3)	8 (Level 2)	A3B3C2

The mechanical properties, of the developed composites such as tensile strength, tensile modulus, and hardness, were determined. First, high-density polyethylene (HDPE) was used to fabricate the sample. Experiments R_1-R_9 were performed with three different natural fibers reinforced in high-density polyethylene (HDPE) with variations in the weight percentage and injection pressure of the injection moulding machine according to the fabrication plan.

Fractional factorial designs using orthogonal arrays were used to determine optimum levels. The optimal injection moulding process parameters were determined to reduce the shrinkage defect in the moulding of a hybrid composite of HDPE reinforced with three natural fibers. Three levels of processing parameters and the L9 orthogonal array were selected for the study. The process parameters and levels are listed in Table 5, and the L9 orthogonal array is presented in Table 6. The input parameters selected were the melting temperature, refilling pressure, and cooling time of the material. Shrinkage was selected as the output variable.

Preparation of Batches for Fabrication Process

After oven drying, these fibers were cut into short lengths between 5 mm and 10 mm. Short fibers in this length range are well suited for injection moulding because they flow readily through the runner-gate system without bridging and are distributed isotropically within the mold cavity. After drying the fibers in the oven, they were packed in plastic bags to prevent moisture. Before the material enters the injection moulding machine, one –one kg material batches are prepared according to Table 4. The weights of each batch material were calibrated using a weighing machine, and the prepared material samples were packed in plastic bags after marking with a permanent marker. After the weight calibration of all the batches, they were mixed separately with the help of a stick in a plastic bucket. During the mixing of batches, 1% by weight of silane, a coupling agent S-69, was added to the mixture for good bonding of the fiber in the HDPE matrix. The batch material was then used to fabricate composite samples. Silane was purchased from Mahaveer Chemical Private Limited, New Delhi.

Samples Preparation

The composite specimens for the tensile and hardness tests were prepared using an injection-moulding machine (Electronica 70–90 ton machine model number 1656) at CIPET, Amritsar, Punjab. The dried material batches were separately fed into an injection- moulding machine through a hopper for specimen preparation. The feeding of batches occurs with the help of force into an insert mold cavity, where it cools and hardens to the shape of the mold. The geometry and dimensions of the tensile, tensile modulus, and hardness specimens were in accordance with the ASTM D638 and ASTM D2240 standards.

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Composites Testing and Characterisation

Tensile Strength and Tensile Modulus Testing of Fabricated Specimens

A total of nine composites were moulded with the reinforcement of different fibers with varying weight percentages in HDPE injected at varying injection pressures, and their properties were tested and analyzed. Therefore, for nine composites, a total of 27 specimens were moulded for the tensile test (Three similar specimens were moulded for each composite). The results were obtained by taking the average of three readings obtained by testing similar specimens. Before tensile testing, all specimens were conditioned in an environmental test chamber (KASKO Industries, Pune) for 40 h at 23º C and 50% RH. Tensile testing of the fabricated dumbbell-shaped specimens was performed according to the ASTM D638 (2010) standard using a universal testing machine (Model: SS UTM 1205, Capacity: 250 kN, Make: PSI Sales Pvt. Ltd.) available at CIPET, Amritsar, India. The tensile strength and tensile modulus of a particular specimen were estimated by taking the average of the readings obtained by testing three similar tensile specimens, and the analysis was performed using MINITAB 18 software.

Hardness Testing of Fabricated Specimens

For hardness testing, nine specimens were moulded using an injection- moulding machine with the reinforcement of three different fibers with varying fiber contents at varying injection pressures. In the present work, the hardness properties were measured using a Durometer Shore D, DIN 53505 model hardness tester. The ASTM standard test method for measuring the hardness properties of fiber-resin composites is ASTM D2240. The respective hardness values of the different specimens were noted directly from the dial indicator by placing the specimens on a flat surface and forcing the indentor into the surface. The hardness of a particular specimen was estimated by averaging the hardness values measured at three different locations of the specimen of each composite type.

Shrinkage Measurement

Shrinkage measurement was performed on rectangular moulded specimens (dimension 162.3 mm × 121.8 mm × 3.20 mm) of JSHHD (Jute, Sisal, Hemp - HDPE) Hybrid composite with 6% weight proportion of each natural fiber reinforced in HDPE. Rectangular specimens were fabricated using an injection- moulding machine. The experiments were performed according to the ASTM-D955 standard. The length and width of the moulded rectangular plaques were measured using a Vernier caliper with an accuracy of ± 0.001 mm. Shrinkage is defined as the difference between the size of the mould cavity and the size of the finished part divided by the size of the mould.

Analysis of Variance (ANOVA)

ANOVA was performed to determine the percentage contributions of fiber type, fiber loading, and injection pressure to the tensile strength, tensile modulus, Shore-D hardness, and shrinkage. Factor significance was evaluated using F-ratios at a 95% confidence level, with p-values < 0.05 indicating a statistically significant effect.

List of Abbreviations

The list of abbreviations used in the study is shown in Table 7.

RESULTS AND DISCUSSION

Effect of Hybridization on Tensile Strength and Tensile Modulus

The tensile strengths of the fabricated composites are listed in Table 8. Experiments 1 to 3 represent JHD (Jute-HDPE) composites, 4 to 6 represent JHHD (Jute, Hemp-HDPE) composites, and 7 to 9 represent JSHHD (Jute, Sisal, Hemp-HDPE) composites.

Table 7. 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
S_k	Shrinkage

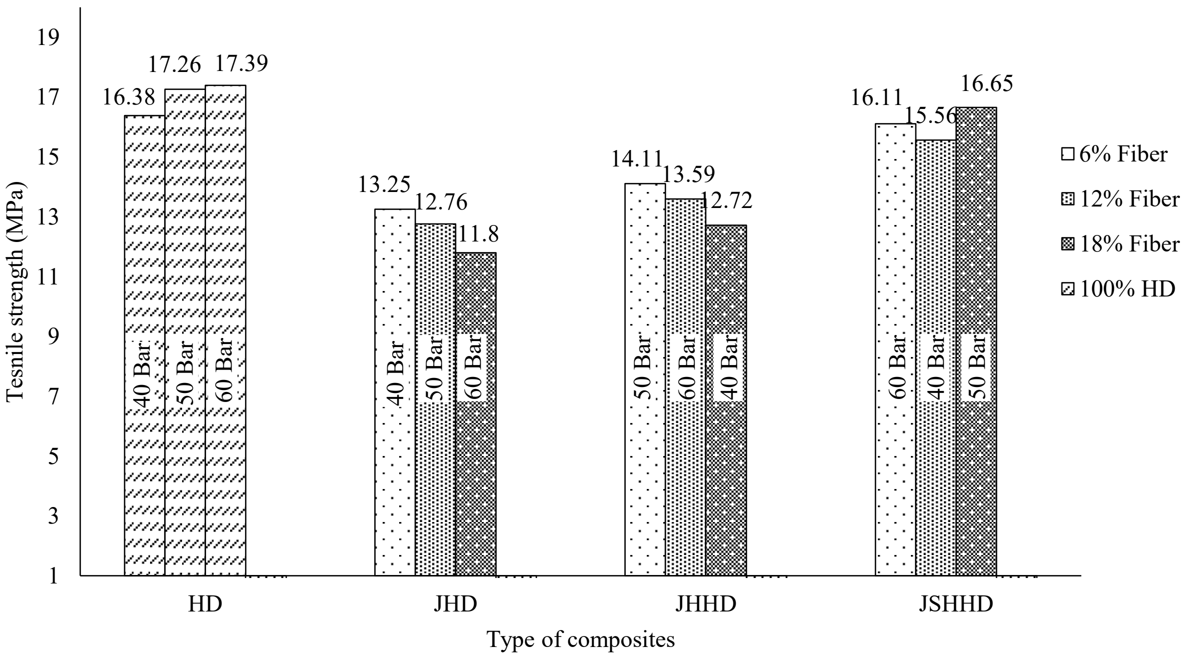

Figure 2. Tensile strength of the developed composites.

It has been investigated that the tensile strength of JHD composite lie in the range of 11.80–13.25 MPa. Similarly, the tensile strength of the JHHD composite varied from 12.72 MPa to 14.11 MPa. For the hybrid composite, the JSHHD tensile strength lies in the range of 14.65 –16.11 MPa. All variations in the values depend on the composite fabrication according to the design methodology. A comparison of the tensile strengths of various fabricated composites, namely Jute-HDPE, Jute-Hemp-HDPE, and Jute-Sisal-Hemp-HDPE, with different types of reinforcements at different injection pressures is presented in Figure 2.

Statistical analysis Table 8 shows the tensile strength of the single-fiber (jute) and hybrid composites (jute and hemp fibers). It is observed in Experiment No 4 that, the incorporation of hemp fiber into jute fiber composites led to a substantial increase in tensile strength. The tensile strength of hybrid composite with 6% fiber (jute and hemp fiber) injected at pressure of 50 Bar is higher than the value obtained in

Experiment No 1, the composite with 6% fibers (Jute fibers only) injected at a pressure of 40 Bar. The tensile strength increased from 13.25 MPa to 14.11MPa. Furthermore, on comparing the tensile strength of 100% HDPE, it was observed that increasing the injection pressure slightly increased the tensile strength. It further increased with the reinforcement of different fibers and an increase in the injection pressure. It is observed that on incorporation of one more fiber sisal in JHHD composite a new composite JSHHD was fabricated and It was found that the with addition of two more fiber in jute significantly change the tensile strength. It is observed that on increasing injection pressure from 40 Bar to 60 Bar and replacing single fiber (Jute) with three different fibers (Jute, Sisal and Hemp), while keeping the weight percentage unchanged in Experiment No 7 the tensile strength of hybrid composite increases by 21.58 %. Similarly, it was observed in the JHD, JHHD, and JSHHD composites that while comparing the tensile strength of these three composites with each other, there was an increase in tensile strength with the reinforcement of different fibers in HDPE injected at varying injection pressures. Thus, a positive effect of hybridization was observed on the tensile strength. However, as the fiber loading was increased from the JHD composite, it decreased from14.11 MPa to 12.72 MPa with the addition of hemp to the mould of the JHHD composite, and it decreased dramatically with an increase from 16.11 MPa to 14.65 MPa with the incorporation of Sisal in Jute and Hemp to fabricate the JSHHD hybrid composite.

It was also observed that increasing the fiber content in the hybrid specimens decreased the tensile strength of all the fabricated composites. It is observed from Experiments No 7, 8, and 9 that hybrid composites reinforced with varying percentages of Jute, Sisal and Hemp fibers into the HDPE matrix with varying injection pressures reduce the tensile strength compared to 100% pure HDPE. The results summarized in Figure 2 show that the tensile strength of the composite decreased with an increase in the fiber content compared to the specimens made of HDPE alone. One of the reasons why the tensile strength of the fiber-reinforced composites is lower than that of the specimen made of HDPE alone could be due to the poor adhesion between the matrix and the fibers, as a results the fibers do not share the load. Moreover, owing to the existence of the gating system in the center of the mold, the fibers were randomly aligned in the specimen apart from bending and curling and were mainly distributed in the middle of the specimen. Hence, the reinforcement did not play a positive role in improving the tensile strength of the composites.

The evaluated tensile modulus of all the fabricated composites are presented in Figure 3. The tensile modulus of the JHD composite decreased with the reinforcement of Jute fiber in HDPE. It was evaluated that in the JHD composite, there was a decrease in the tensile modulus with an increase in the fiber loading wt% and with an increase in injection pressure. As fiber loading increased from 6% to 18 %, the tensile strength decreased. The tensile modulus ranged from 0.79 to 0.92 GPa. Reinforcement of hemp in JHD led to the JHHD composite, and the value of the tensile modulus increased as compared to JHD. Similar to the JHD composite, the tensile modulus decrease with an increase in the reinforcement of fiber loading from 6% to 18% wt%. However in case of hybrid composite JSHHD, the evaluated value of the tensile modulus ranged between 1.03 and 1.08, which is highest among three fabricated composites, which shows that with hybridization of different fibers with different wt% led to a dramatic change in the tensile modulus. In the JSHHD composite, the maximum value of the tensile modulus was obtained at an injection pressure of 40 bar with a fiber loading of 12 wt%. However, as the fiber loading and injection pressure further increased from 12 % to 18 % and 40 to 50 Bar, respectively, the tensile modulus of the hybrid composites decreased. The tensile modulus was the highest in the hybrid composite JSHHD among the other fabricated composites, but low compared to the specimens made of HDPE alone.

Effect of Hybridization on Hardness

Hardness is the resistance offered by a material to indentation cutting or scratching. Hardness is an essential property that controls the wear resistance of a material. The results obtained from various specimens fabricated with the reinforcement of three different fibers with varying fiber contents at varying injection pressures are summarized in Table 8.

Table 8. Tensile, tensile modulus and hardness properties results.

Exp. No.	Fiber type A	Fiber loading B	Injection pressure C	Tensile strength (Mpa)	Tensile modulus (Gpa)	Hardness (SHD)
1	1	1	1	13.25	0.92	68
2	1	2	2	12.76	0.84	68
3	1	3	3	11.80	0.79	65
4	2	1	2	14.11	1.01	67
5	2	2	3	13.59	0.94	67
6	2	3	1	12.72	0.84	68
7	3	1	3	16.11	1.06	66
8	3	2	1	15.56	1.08	67
9	3	3	2	14.65	1.03	68

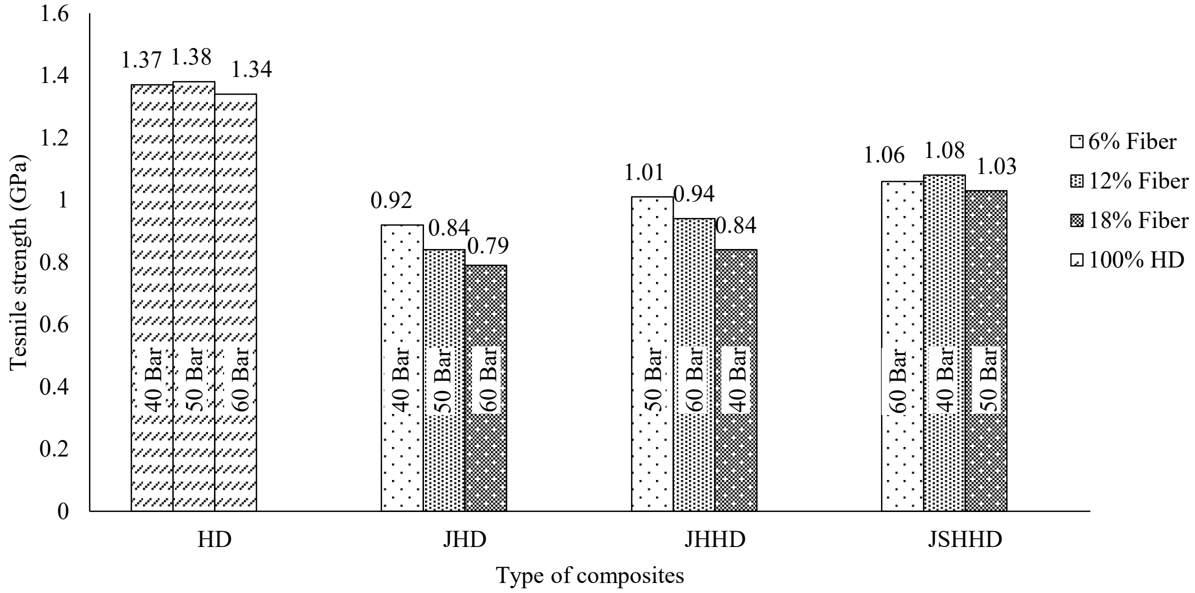

Figure 3. Tensile modulus of the developed composite.

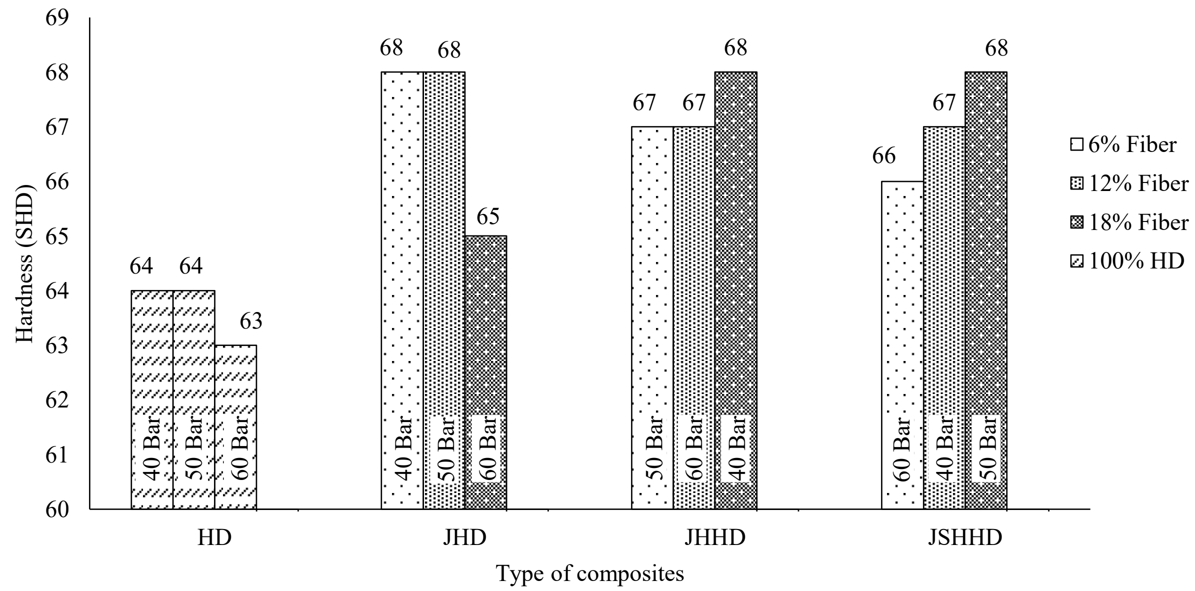

Figure 4. Hardness of developed composite.

It was observed that the pure HDPE matrix had the lowest hardness, as shown in Figure 4, compared to all the fabricated composites in this study. Statistical analysis Table. 8 shows that the hardness of HDPE improved with increasing the fiber content and injection pressure. It has been observed the hardness of pure HDPE decreases with increasing injection pressure. The hardness of the hybrid composite (JSHHD) increased by up to 7.9 % compared to that of Pure HDPE.

It was found that in the JHD composite, the hardness was 68 Shore-D with 6 wt% and 12 wt% of fiber at 40 and 50 bar injection pressures. However, when 18 wt% of fiber and at an injection pressure of 60 bar, there was a decrease in hardness of up to 4.6%, which shows that reinforcing a single fiber (jute) in HDPE showed that with an increase in the fiber content and injection pressure in the JHD composite, the hardness decreased. Similarly, it was observed in the JHHD and JSHHD composites that the hardness decreased with an increase in the injection pressure of the injection-moulding machine, whereas the hardness increased with increasing fiber content. A significant change in the hardness was observed with the reinforcement of different fibers in HDPE. Therefore, a positive effect of hybridization was observed on hardness.

Shrinkage Measurement and Optimization of Processing Parameters of Injection Moulding Machine

The specimens were measured in the flow direction to measure their length and in the x-flow direction to measure their width. The measurements of length in the flow direction are L1, L2, and L3, whereas the measurements of width in the x-flow direction are W1, W2, and W3, as shown in Figure 5. Shrinkage was calculated using Equations (1) and (2).

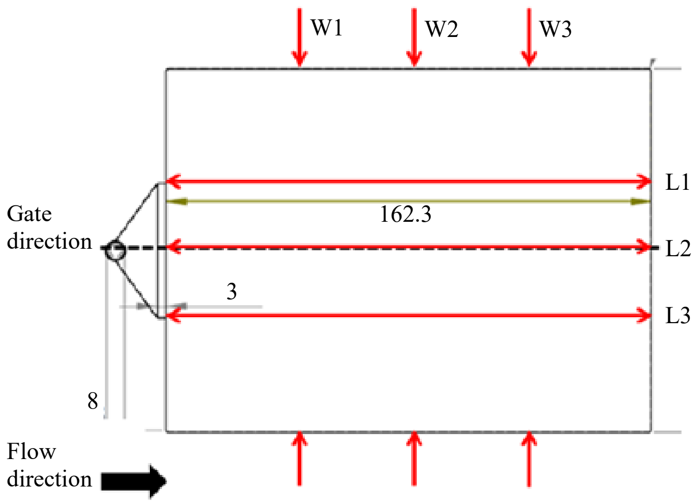

Figure 5. Shrinkage measurement locations in a rectangular plaque.

Table 9. Shrinkage results.

Exp. No.	Melting temp A	Refilling pressure B	Cooling time C	Flow direction shrinkage percentage (%)	x-flow direction shrinkage percentage (%)
1	1	1	1	1.575	1.578
2	1	2	2	1.500	1.502
3	1	3	3	1.25	1.252
4	2	1	2	1.437	1.438
5	2	2	3	1.50	1.502
6	2	3	1	1.625	1.628
7	3	1	3	1.375	1.377
8	3	2	1	1.40	1.403
9	3	3	2	1.78	1.781

Shrinkage in flow direction, Ls = [Lm–Mean (L1…L3)]/ Lm * 100 % (1)

Shrinkage in x-flow direction, Ws = [Wm–Mean (W1…W3)]/ Wm * 100 % (2)

Where,

Lm and Wm are the length and width of the plaque mold, respectively.

The outcomes of the shrinkage of the fabricated composites are summarized in Table 9.

Experimental Design

This section discusses how the properties of a component are affected by the selected parameters. In this section, the optimal values of the parameters that influence the properties of the composites are discussed. The better the parameters match the mechanical properties, the better the component will perform. Hence, it is important to determine the contribution of each parameter in fabrication process.

ANOVA was used to determine the most significant parameter, Analysis of variance (ANOVA) is a statistical tool widely used to determine the statistical significance of parameters. This enables us to determine the specific parameters that require modification to achieve the desired performance. The determination of the optimal parameters, based on the mean and signal-to-noise (SN) ratios, responses, and characteristics, was performed by analyzing the response plots and analysis of variance tables.

Experimental Responses

The current investigation entailed the fabrication and characterization of composites through the implementation of the Taguchi technique. This helps to achieve the effects of the selected parameters on the measured response. The mechanical characterization results are listed in Table 8. using the experimental responses. Each experiment was conducted three times to derive the average value or mean of the results, and data analysis was performed using the MINITAB 18 software.

Effect of Selected Parameters, ANOVA and Significance of Parameters on Tensile Strength and Tensile Modulus

To analyze the impact of the chosen parameters on the tensile properties, experiments were performed using the L_9 orthogonal array. The Average values of the tensile strength with respect to each parameter at levels 1, 2, and 3 for both the mean responses and S/N ratio response with larger is better characteristics are presented in Figures 6(a) and 6(b). A represents the fiber type, B represents the fiber loading, and C represents the Injection Pressure, as shown in Table 8. The tensile strength decreased with an increase in the fiber content. It is well known that the tensile strength of developed hybrid JSHHD composite is less than 100% pure HDPE. In this study, the tensile strength of the fabricated hybrid composites was analyzed with 6 wt% fiber content. The S/N and mean data in Tables 10 and 11 contain the tensile strength response values.

The delta and rank values are presented in Tables 10 and 11, respectively. The second last and last rows of Tables 10 and 11 show the delta and rank values. The rank assigns a level of significance to the individual parameters in relation to their influence on the response variable. Evidently, the parameter analysis indicates a maximum delta value of 1.77, which concurs with the highest elevated rank of 1.The findings indicate that fiber loading B has the most significant impact on tensile strength. The present investigation revealed that, as shown in Table 10, the signal-to-noise ratio is discerned to verify the delta and rank values, which are evidently observed to exhibit the highest values, where delta and rank values are highest, from which we can verify the signal-to-noise ratio.

Table 10. Response of S/N ratio for tensile strength.

Level	A	B	C
1	23.19	22.00	22.79
2	22.87	22.58	22.81
3	22.28	23.77	22.75
Delta	0.91	1.77	0.06
Rank	2	1	3

To determine the comparative importance of the selected parameters on the tensile strength, an analysis of variance (ANOVA) table was generated. Table 12 shows the significant and non-significant process parameters for the tensile strength. The importance of the selected parameters on the performance of the results is indicated in the last column. If the p-value is less than 5%, this indicates a highly significant parameter, as presented by many authors. This analysis also revealed the same, with a p-value of less than 5 %, indicating a highly significant parameter. From the analytical data, it was observed that A and B, which represent the fiber type and fiber loading, respectively, are significant parameters for tensile strength, whereas point C, which represents the injection pressure, is not a significant parameter.

As shown in Figures 6(a), the combination of the third level of fiber (A_3–JSH), first level of fiber loading (B_1–6 wt%), and second level of injection pressure (C_2–50 Bar) exhibited the highest tensile strength value.

Similarly, the S/N ratio in Figures 6(b) also indicates the same (A_3, B_1, C_2) for the maximum tensile strength in the composite characterization. These evaluated values are the optimum parameters for achieving the maximum tensile strength.

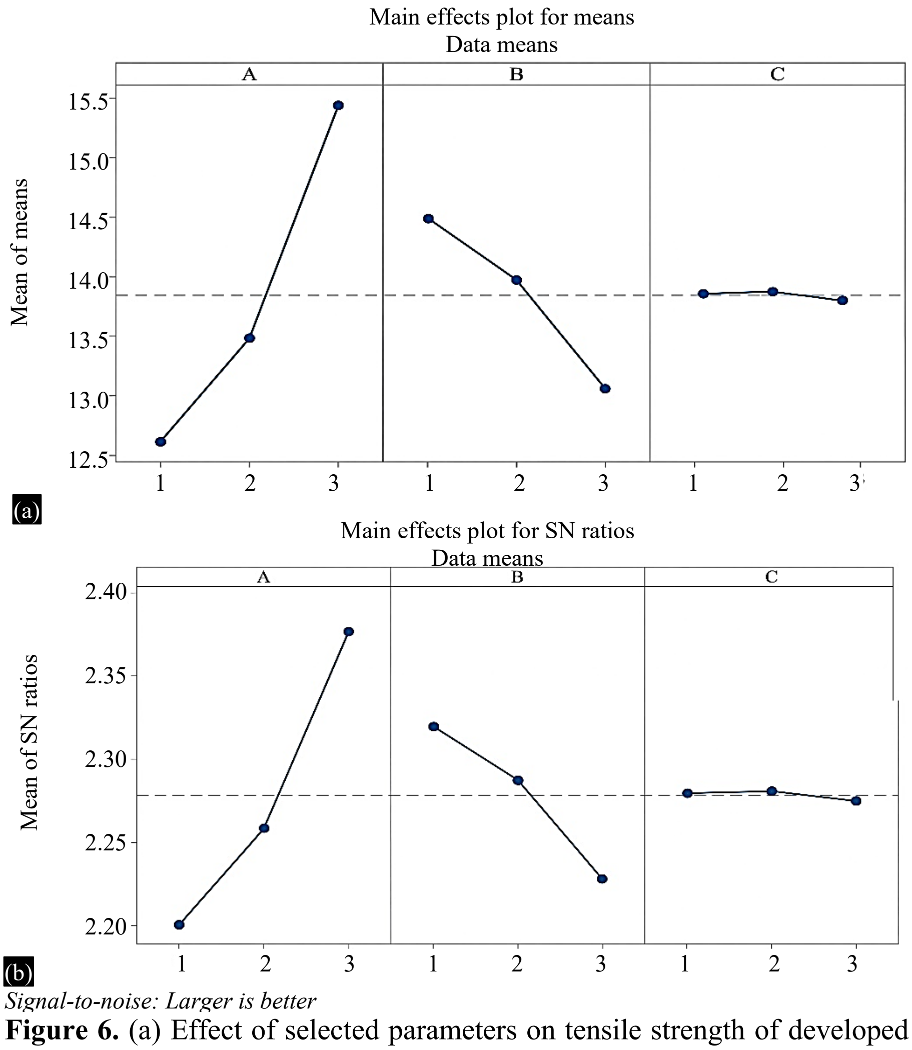

Figure 6. (a) Effect of selected parameters on tensile strength of developed composites (mean data); (b) Effect of selected parameters on tensile strength of developed composites (S/N Data). (A) Fiber type; (B) Fiber loading; (C) Injection pressure.

Table 11. Response of average for tensile strength.

Level	A	B	C
1	14.49	12.60	13.84
2	13.97	13.47	13.84
3	13.06	15.44	13.83
Delta	1.43	2.84	0.01
Rank	2	1	3

Table 12. ANOVA for Tensile Strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	9.379	9.379	4.692	4.28	0.033
B	2	8.789	8.789	4.396	3.99	0.038
C	2	1.513	1.513	0.758	0.71	0.520
Error	20	22.121	22.121	1.116		
Total	26	41.802				

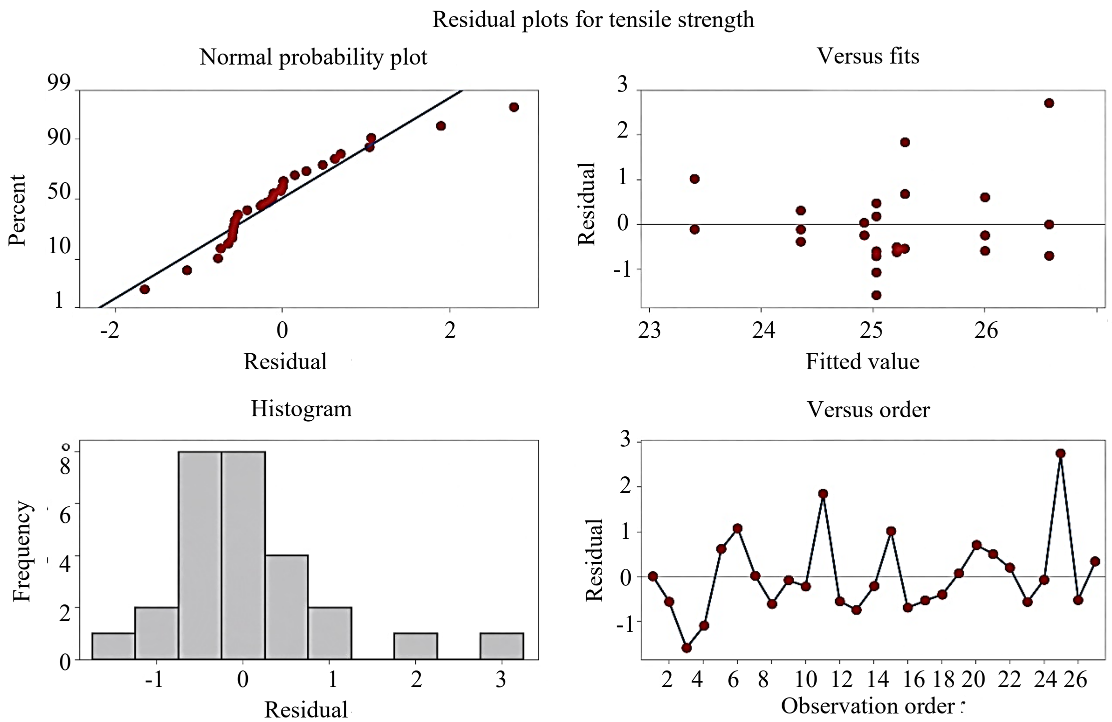

Figure 7. The residual plot for the tensile strength.

The residual plot (Figure 7) for the tensile strength shows that all residues drop to the trend line in normal probability plots. The residuals were generally distributed, and the histogram chart was normal in nature, as shown in Figure 7, and the residuals were scattered randomly around the zero line in the residuals versus the fitted values. The residuals have no clear-cut pattern, which indicates that the data collection is in order.

The average values of the tensile modulus with respect to each parameter at levels 1, 2, and 3 for both the mean responses and S/N ratio response are presented in Figures 8(a) and 8(b). The characteristics of a larger S/N ratio response are better, as presented in Table 13, where A represents the fiber type, B represents the fiber loading, and C represents the Injection Pressure.

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Table 13. Response table for S/N ratio for tensile modulus

Level	A	B	C
1	-0.0439	-1.42871	-0.52339
2	-0.46113	-0.65514	-0.39041
3	-1.10171	0.47711	-0.69293
Delta	1.05781	1.90582	0.30252
Rank	2	1	3

Table 14. Response table for average for tensile modulus.

Level	A	B	C
1	0.9967	0.8500	0.9467
2	0.9533	0.9300	0.96
3	0.8867	1.0567	0.93
Delta	0.11	0.2067	0.03
Rank	2	1	3

Table 15. ANOVA table for tensile modulus.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.00446	0.00446	0.00267	0.28	0.640
B	2	0.07583	0.07583	0.03835	3.97	**0.032**
C	2	0.00028	0.00028	0.00058	0.06	0.890
Error	20	0.19241	0.19241	0.00955		
Total	26	0.27298				

The highest delta value indicates the greatest influence. As shown in Table 13, the highest delta value is 1.90582, and the highest rank of B (fiber loading) is 1, which shows that the fiber loading wt % has the greatest influence on the tensile modulus. It is also examine that the delta and rank values are also verified from the mean data Table 14 where delta and rank values are highest and accordingly the highest rank B (fiber loading) factor can influence more on tensile modulus of the fabricated composites. Figure 7 shows the residual plot for the tensile strength.

From Figures 8 (a) and 8 (b), it can be observed that the tensile modulus decreases with an increase in the level of fiber loading wt %. It is also investigated from the mean data in Figure 8 (a) that the third level of fiber type JSH, the first level of fiber loading 6 wt. % and second level of injection pressure 50 Bar leads to the greatest value of tensile modulus. Similarly, The S/N Ratio analysis, shown in Figure 8 (b), also shows the same (A_3, B_1, C_2) for the maximum tensile modulus in the composite characterization.

The significant and insignificant parameters for the tensile modulus are presented in Table 15. It was observed that B (fiber loading) is a significant parameter for the tensile modulus, whereas A and C, which represent fiber type and injection pressure, respectively, are not significant parameters for the tensile modulus.

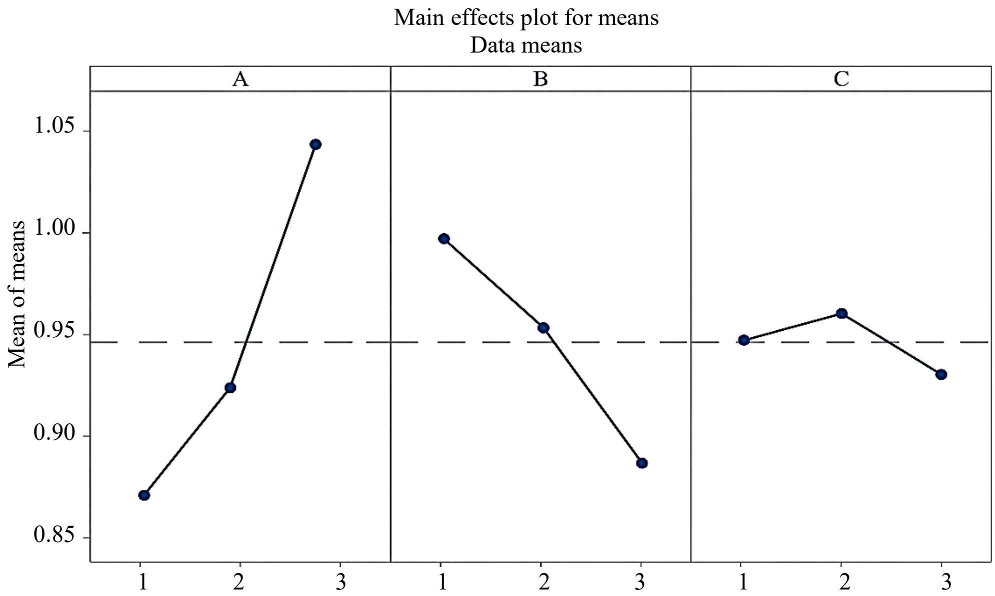
The residual plot (Figure 9) for the tensile modulus shows that all the residues are close to a straight line in the normal probability plots. The residuals did not exhibit any particular trends. Therefore, the data collection errors were negligible.

Effect of Selected Parameters, ANOVA and Significance of Parameters on Hardness

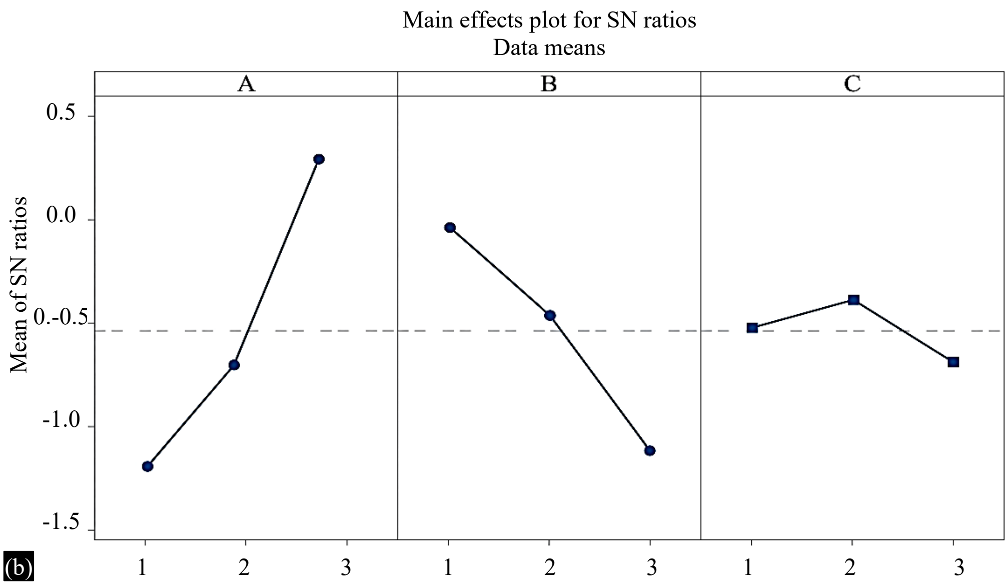
The experimental results of the hardness are presented in Table 8. In Figures 10 (a) and 10 (b), the values of hardness for each parameter at three levels for responses and S/N ratio data larger is better characteristic are plotted. It can be from Figures 10 (a) and 10 (b) that the third level of fiber type (A_3), which is JSH, second level of fiber loading (B_2) that is 12 wt% and second level of injection pressure (C_2), which is 50 Bar, provide the largest value of hardness.

Tables 16 and 17 show the ranks of the effective parameters for hardness. It has been noticed that the highest rank is obtained for B (Fiber Loading). The second highest rank is obtained for both A (fiber type) and C (Injection Pressure).

Therefore, the parameter with the highest influence on the hardness properties of the different composites is the fiber loading. This was evaluated using ANOVA, as shown in Table 18. It was found that fiber loading is a significant parameter for hardness, whereas fiber type and injection pressure are less significant.



(a)



(b)

Signal-to-noise: Larger is better

Figure 8. (a) Effect of Selected Parameters on Tensile Modulus of Developed Composites (mean Data); (b) Effect of selected parameters on tensile modulus for developed composites (S/N data).

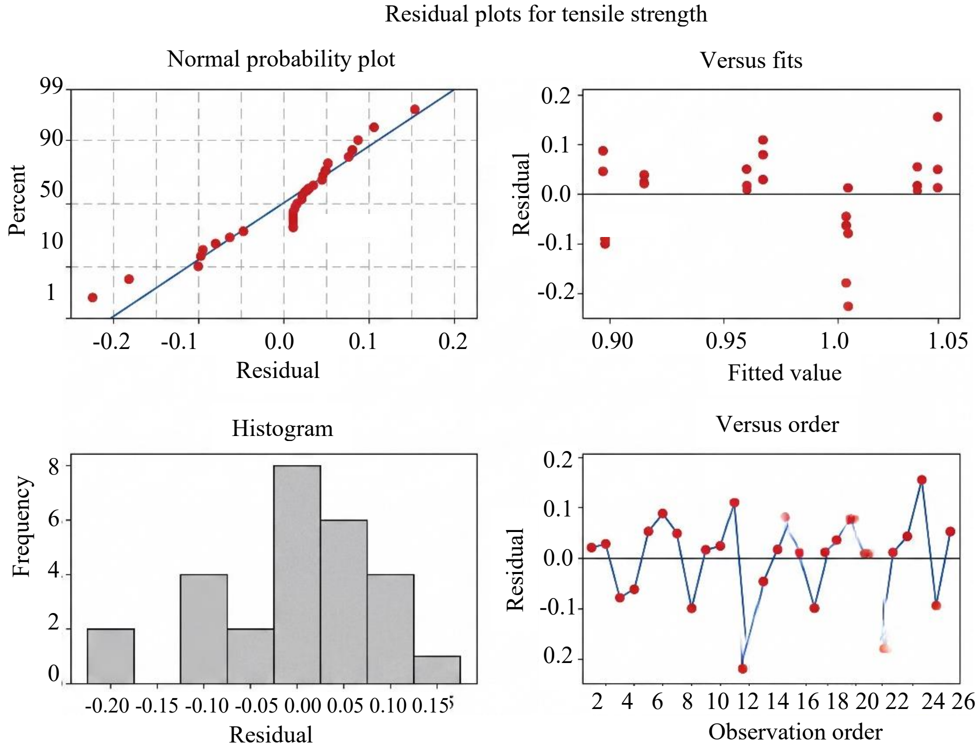


Figure 9. The residual plot for tensile modulus.

Table 16. Response of S/N ratio for hardness.

Level	A	B	C
1	36.52	36.61	36.52
2	36.56	36.61	36.56
3	36.52	36.39	36.52
Delta	0.04	0.22	0.04
Rank	2.5	1	2.5

Table 17. Response of average for hardness.

Level	A	B	C
1	67.00	67.67	67.00
2	67.33	67.67	67.33
3	67.00	66.00	67.00
Delta	0.33	1.67	0.33
Rank	2.5	1	2.5

Table 18. ANOVA for hardness.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	2.299	2.299	1.151	0.33	0.748
B	2	1.299	1.299	1.151	0.33	**0.048**
C	2	4.745	4.745	2.374	0.66	0.554
Error	20	76.973	76.973	3 .858		
Total	26	85.316				

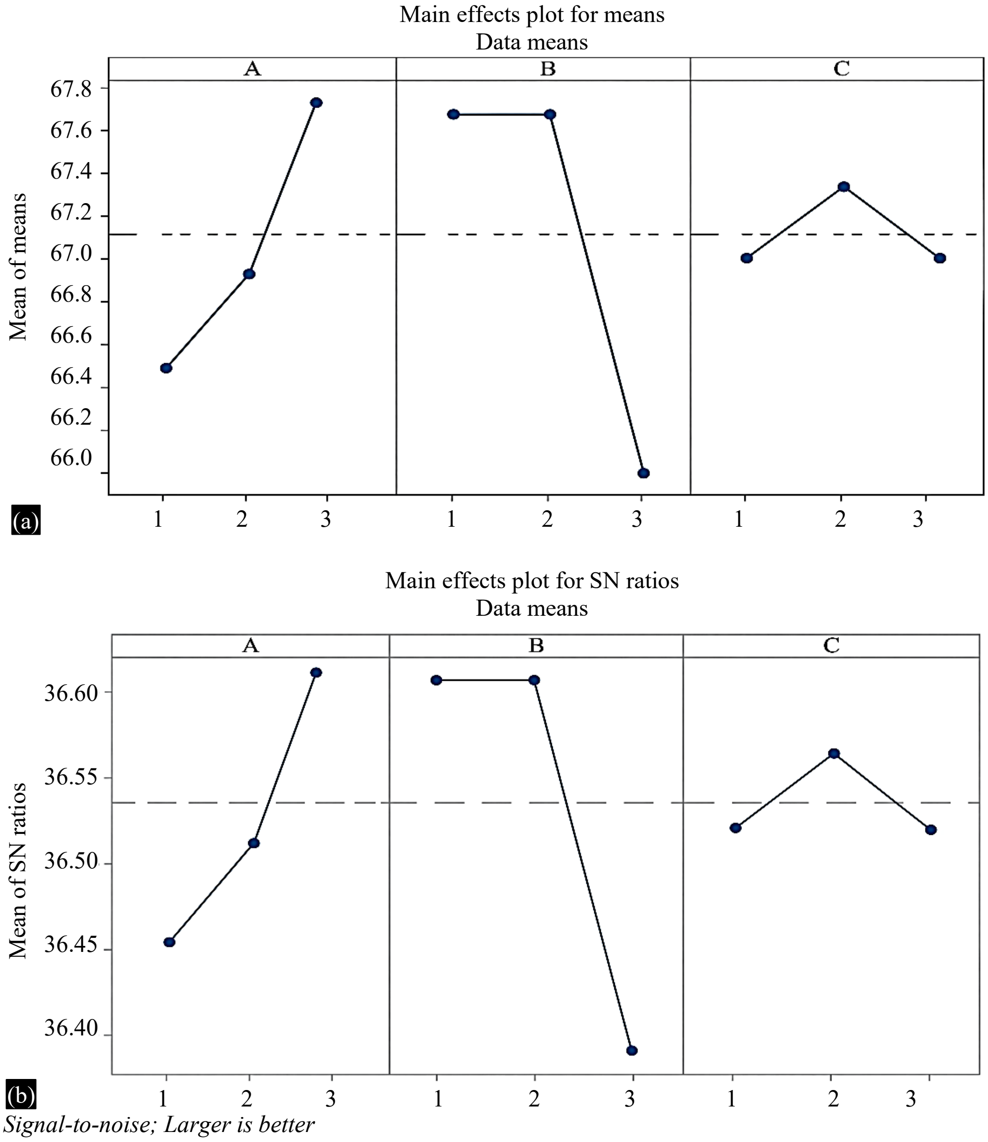


Figure 10. (a) Effect of selected parameters on hardness for developed composites (Mean Data); (b) Effect of selected parameters on hardness for developed composites (S/N data).

It is evaluated from Figure 11 that the residual plot for the hardness indicates that in normal probability plots residues are close to the straight line. Therefore, there were no errors in data collection.

Effect of optimizing Selected Parameters, ANOVA and Significance of Parameters on Shrinkage Defect

Effect of optimizing Selected Parameters on Shrinkage Flow Direction

To analyze the impact of the chosen parameters on the shrinkage, experiments were performed using the L_9 orthogonal array for the flow and x-flow directions. The Average values of the shrinkage percentage calculated with respect to each parameter at levels 1, 2, and 3 for both mean responses and S/N ratio response with smaller is better characteristics are presented, where A represents Melting Temperature, B represents Refilling Pressure and C represents cooling time, as shown in Table 9**.**

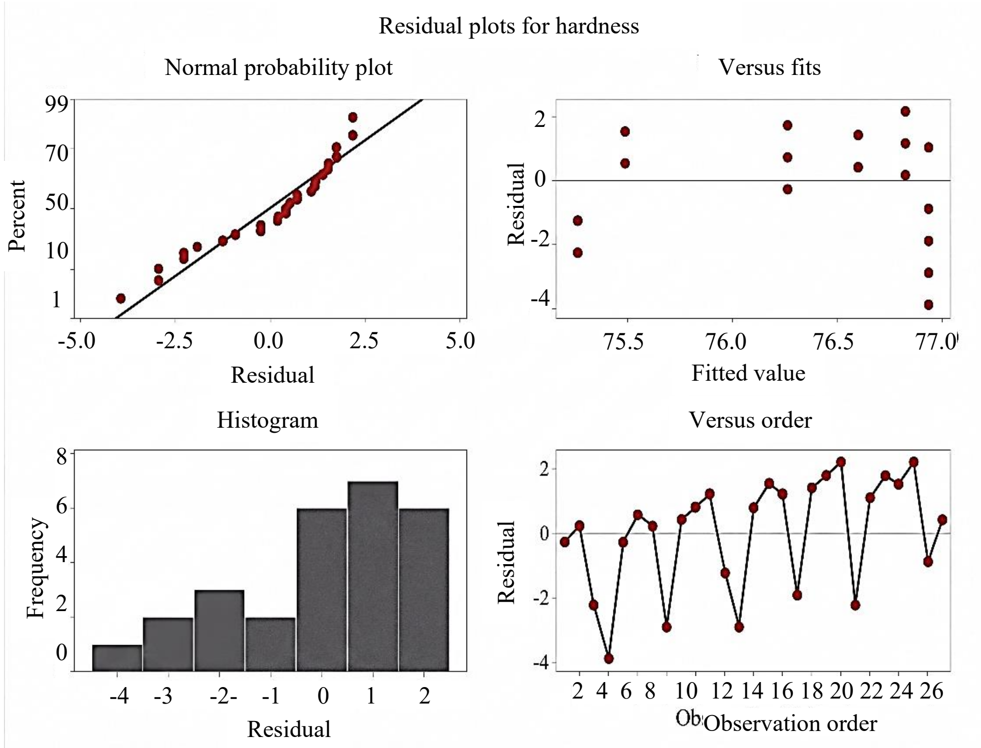


Figure 11. The residual plot for hardness.

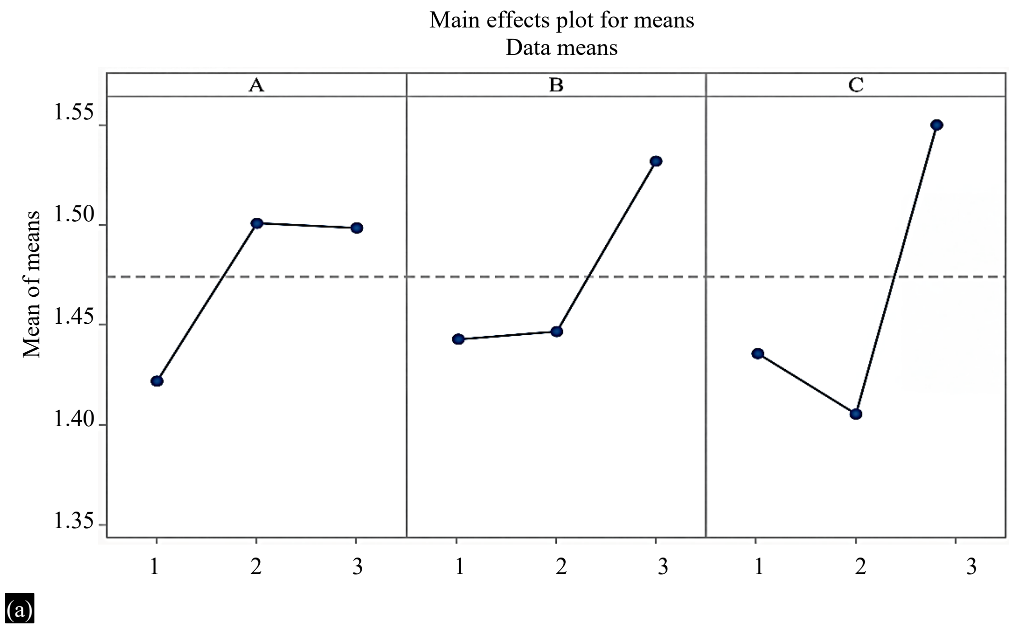
Table 19. Response of S/N Ratio for flow direction Shrinkage.

Level	A	B	C
1	-3.167	-3.013	-3.581
2	-3.203	-3.514	-3.781
3	-3.606	-3.449	-2.614
Delta	0.439	0.501	1.167
Rank	3	2	1

Table 20. Response of average for flow direction shrinkage.

Level	A	B	C
1	1.422	1.443	1.513
2	1.501	1.447	1.552
3	1.498	1.532	1.355
Delta	0.079	0.089	0.197
Rank	3	2	1

The delta and rank values of the shrinkage flow direction are listed in Tables 19 and 20, respectively. The second last and last rows of Table 19 show the delta and rank values. The rank assigns a level of significance to individual parameters in relation to their influence on the response variable. Evidently, the parameter analysis indicates a maximum delta value of 1.167, which concurs with the highest elevated rank of 1. The findings indicate that Cooling Time C has the most significant impact on the shrinkage flow direction of the material. The present investigation revealed that, as shown in Table 19, the signal-to-noise ratio is discerned to verify the delta and rank values, which are evidently observed to exhibit the highest values, where delta and rank values are highest, from which we can verify the signal-to-noise ratio. From Figures 12(a) and 12(b), it was evaluated that a melting temperature of 190°C, Refilling pressure of 85 MPa, and cooling time of 11 s resulted in minimum shrinkage in the flow direction.



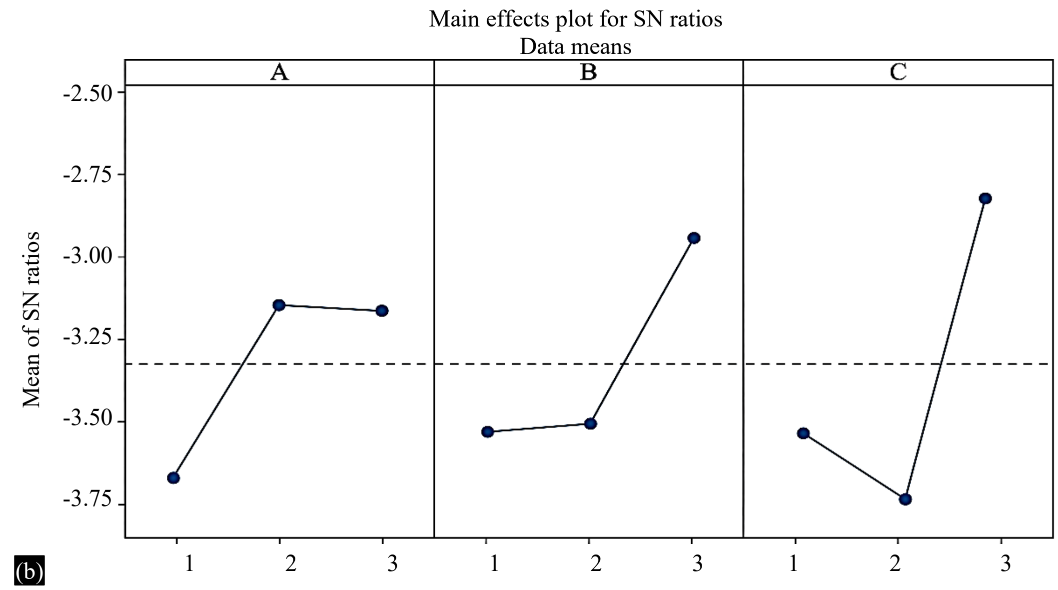


Figure 12. (a) Effect of selected parameters on flow direction shrinkage (mean data); (b) Effect of selected parameters on flow direction shrinkage (S/N data). (A) Melting Temperature; (B) Refilling Pressure; (C) cooling time.

Effect of optimizing Selected Parameters on Shrinkage X-Flow Direction

The delta and rank values of the shrinkage x-flow direction are listed in Tables 21 and 22, respectively; The second last and last rows of Table 21 show the delta and rank values, respectively. Evidently, the parameter analysis indicates a maximum delta value of 1.169, which concurs with the highest elevated rank of 1. The findings indicate that Cooling Time C has the most significant impact on the shrinkage x-flow direction of the material. From Figures 13 (a) and 13 (b), it was evaluated that a melting temperature of 190^{O}C, Refilling pressure of 85 MPa, and cooling time of 11 s resulted in minimum shrinkage in the x-flow direction.

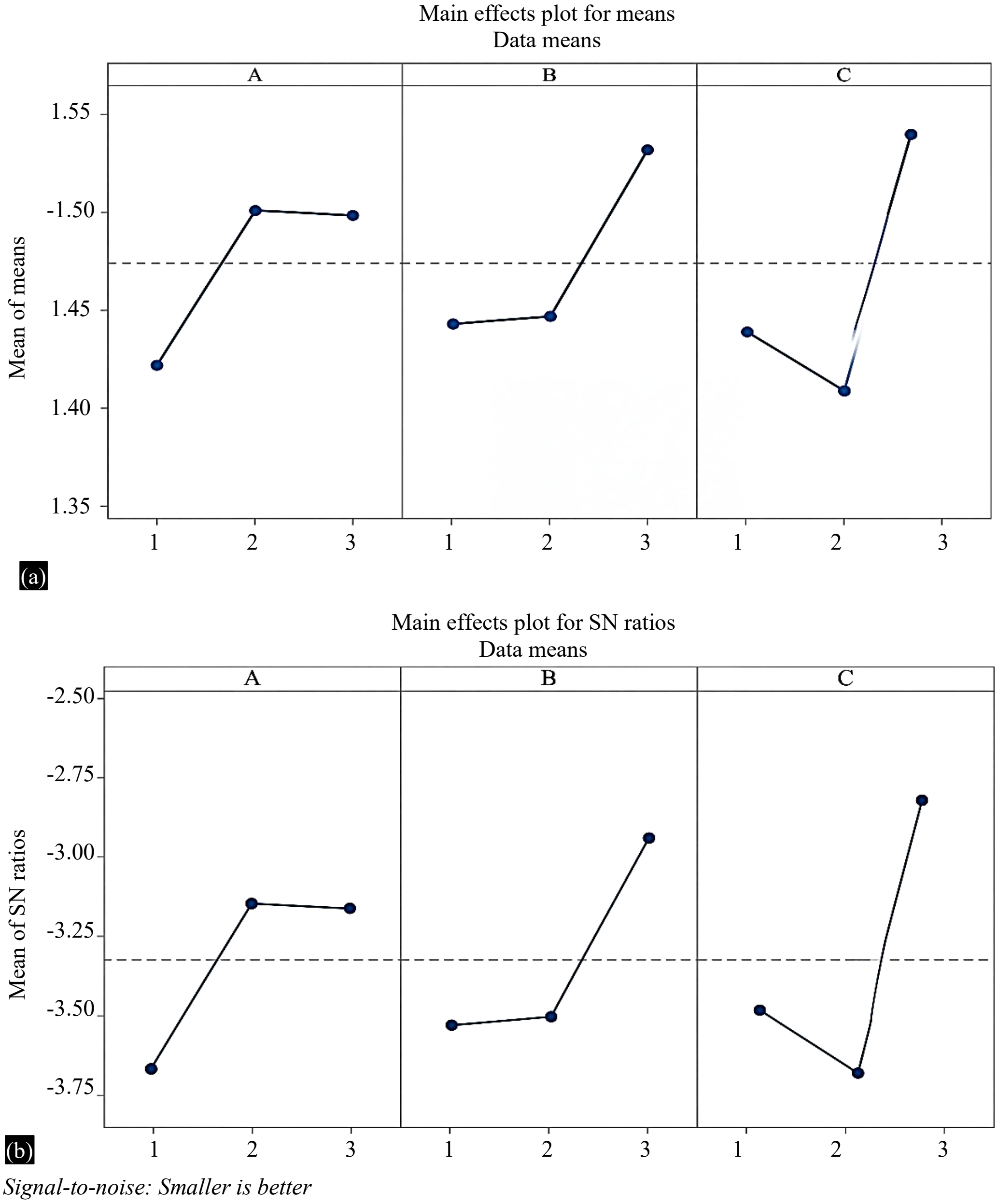


Figure 13. (a). Effect of selected parameters on x-flow direction shrinkage (mean data); (b). Effect of selected parameters on x-flow direction Shrinkage (S/N Data). (A) Melting Temperature; (B) Refilling Pressure; (C) cooling time.

Table 21. Response of S/N ratio for x-flow direction shrinkage.

Level	**A**	**B**	**C**
1	-3.170	-3.015	-3.584
2	-3.206	-3.517	-3.786
3	-3.609	-3.450	-2.617
Delta	0.439	0.502	1.169
Rank	3	2	1

Table 22. Response of average for x-flow direction shrinkage.

Level	A	B	C
1	1.423	1.442	1.515
2	1.504	1.448	1.553
3	1.501	1.534	1.353
Delta	0.081	0.092	0.200
Rank	3	2	1

Table 23. ANOVA for flow direction Shrinkage.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.00025	0.00025	0.00053	0.03	0.86
B	2	0.00316	0.00316	0.00237	0.25	0.61
C	2	0.07453	0.07453	0.03805	3.94	**0.002**
Error	20	0.19111	0.19111	0.00925		
Total	26	0.26905				

Table 24. ANOVA for x-flow direction shrinkage.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.00028	0.00028	0.00054	0.06	0.88
B	2	0.00318	0.00318	0.00239	0.28	0.64
C	2	0.07455	0.07455	0.03808	3.98	**0.004**
Error	20	0.19114	0.19114	0.00926		
Total	26	0.26915				

ANOVA and Significance of Parameters on shrinkage

To determine the comparative importance of the selected parameters on flow direction shrinkage, an analysis of variance (ANOVA) was conducted. Table 23 shows the significant and non-significant process parameters for the flow direction shrinkage. From the analytical data, it was observed that C, which represents cooling time, is the most significant parameter for shrinkage, and A and B, which represent Melting Temperature and Refilling Pressure, respectively, are not significant parameters.

To determine the comparative importance of the selected parameters on the x-flow direction shrinkage, an analysis of variance table was created (Table 24). From the analytical data, it was observed that C, which represents cooling time, is the most significant parameter for shrinkage, whereas A and B, which represent Melting Temperature and Refilling Pressure, respectively, are not significant parameters.

The results obtained showed less shrinkage in both the flow and x-flow directions. The results obtained indicate that a melting temperature of 190°C, Refilling pressure of 85 MPa, and cooling time of 11 s resulted in minimum shrinkage in the flow and x flow directions. Cooling time was found to be the most significant factor, whereas the Melting Temperature was found to be the least effective factor.

APPLICATIONS

Automotive Interior Parts

Door panels, trunk liners, and instrument panel substrates are well-suited for these composites, as interior components bear no structural load. Natural fibers also eliminate the sharp-end hazard associated with glass fibers during manufacturing and end-of-life processing.

Consumer and household goods

Tools handles, storage crates, and lightweight furniture components benefit from progressive hardness improvement with increasing fiber loading. The bio-based fiber content combined with recycled HDPE offers a marketable sustainability advantage to the product.

Construction and Building Products

Ceiling tiles, partition boards, and cable duct covers require dimensional stability rather than high tensile strength, which these composites offer. The 190°C processing temperature reduces energy costs, whereas the HDPE matrix resists biological degradation in humid environments.

Agricultural Equipment and Packaging

Seed trays, storage panels, and industrial pallets are cost-driven applications that are well served by these composite materials. Locally sourced fiber residues shorten supply chains, and 12–18 wt% fiber loading enhances the hardness and stiffness in packaging applications.

Electrical Enclosures and Sporting Goods

Junction box covers benefit from the stable dielectric properties of HDPE, whereas shrinkage-minimized moulding ensures dimensional accuracy. In sporting goods, the low density of plant fibers offers a weight advantage, and the hybrid JSH configuration improves the batch-to-batch consistency.

CONCLUSION

The experimental results support a coherent and consistent picture of how natural fiber reinforcement modifies the behavior of HDPE in this context. The key observations were as follows:

1. The injection moulding process was proven to be an effective and industrially viable technique for fabricating hybrid natural-fiber-reinforced HDPE composites. The machine facilitated uniform fiber distribution within the matrix and produced dimensionally consistent specimens across all experimental runs, confirming its suitability for processing short natural fiber–thermoplastic blends.
2. Tensile strength and modulus. Both properties declined progressively as the fiber weight fraction increased from 6 to 18 wt%. The reduction in the tensile strength indicates that at higher loadings, the short fibers begin to act as stress concentrators and interrupt the continuity of the matrix rather than reinforcing it effectively. The accompanying drop in the tensile modulus suggests that beyond a certain fiber content, agglomeration and incomplete wetting of fiber bundles weaken the load-transfer mechanism across the fiber–matrix interface. This trend was consistent across all three fiber-type configurations.
3. Shore-D hardness. In contrast to the tensile properties, the surface hardness increased steadily with increasing fiber content. Cellulosic fibers are intrinsically stiffer than the HDPE matrix, and their presence at the specimen surface resists indenter penetration. This result indicates that natural fiber addition can be a useful strategy when improved surface hardness is a design requirement, even in cases where tensile performance is not the primary concern.
4. Optimal injection-moulding conditions for minimum shrinkage. S/N ratio analysis under the smaller-is-better criterion identified the following combination of settings as optimal for minimizing dimensional shrinkage: a melting temperature of 190 °C, a refilling (holding) pressure of 85 MPa, and a cooling time of 11sec.
5. Dominant process variables. ANOVA revealed that fiber loading is the most influential factor governing the mechanical properties of the hybrid composites. Its percentage contribution to the total observed variance was the highest among the three control parameters studied — fiber type, fiber loading, and injection pressure — confirming that the amount of reinforcement present in the matrix has a more decisive effect on composite performance than either the specific combination of fiber species used or the moulding pressure applied.

FUTURE SCOPE

Process Parameter Optimization

In this study, certain parameters were held constant to isolate these three primary factors. Future work should incorporate these variables into the experimental framework using an L18 orthogonal array or Response Surface Methodology, which is better equipped to capture interaction effects that a standard Taguchi main-effects model overlooks.

Fiber Loading and Composition

Because this study examined only 6, 12, and 18 wt% fiber loadings, the exact threshold at which the strength reduction begins to outweigh the hardness improvement remains unclear. Testing intermediate fractions, such as 9 and 15 wt%, would identify this crossover more precisely, while extending beyond 18 wt% would reveal whether the hardness gains persist or diminish because of fiber agglomeration.

Fiber Surface Treatment

Although NaOH alkali treatment was employed in the present work, more advanced coupling agents, such as maleic anhydride grafted polyethylene (MAPE), are known to form stronger chemical bonds at the fiber-matrix interface. Comparing these treatments under uniform processing conditions would help determine whether the observed tensile strength reduction is primarily an interfacial issue or a function of fiber geometry.

Mechanical and Durability Testing

The current study focused on the tensile strength, tensile modulus, and hardness; however, the impact resistance, flexural strength, fatigue behavior, and creep response are equally relevant for practical applications. Furthermore, moisture durability deserves attention, as natural fibers absorb water during service, degrading the fiber-matrix bond. Conducting water absorption tests according to ASTM D570 and subsequently retesting the conditioned specimens would provide a more realistic assessment of long-term composite performance.

Alternative Materials and Sustainability

Substituting or supplementing current fibers with kenaf, flax, bamboo, or pineapple leaf fibers could diversify the property profile, given that each offers a distinct stiffness-surface chemistry balance. On the matrix side, replacing HDPE with polypropylene or polylactic acid (PLA) would clarify how matrix selection influences the overall property trends. PLA, in particular, would yield a fully bio-based composite that aligns with broader sustainability objectives.

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