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A novel mechanical purification approach for *Grewia optiva* Fibre-Reinforced epoxy composites: Effect of fibre geometry on structural performance

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ABSTRACT: Researchers have recently shifted their focus toward natural fibre-reinforced polymer composites due to their superior ecological friendliness and environmental sustainability compared to synthetic counterparts. Among the diverse sources of natural reinforcement, *Grewia optiva* (locally known as Bhimal) has emerged as a promising plant fibre. This study investigates the development of epoxy matrix composites reinforced with short, untreated *Grewia optiva* fibres at lengths of 5 mm, 10 mm, and 15 mm. A key novelty of this research is the mechanical purification of the fibres extracted *via* the traditional water-retting method using an iron strand brush to remove the surface impurities without any chemical treatment. Experimental characterization revealed that these fibres possess an average density of 1.232 g/cm^3. For composite fabrication, the epoxy resin and hardener were mixed in a volume ratio of 100:12. Mechanical testing indicated that a 5 mm fibre length and 30% volume fraction optimize the Ultimate Tensile Strength (62 MPa) and Flexural Strength (119.8 MPa), as this configuration ensures effective stress transfer without structural defects. Conversely, the minimum water absorption was achieved at 5 mm/20% due to reduced hydrophilic content, while the maximum elongation (4.67%) occurred at 5 mm/40%, where shorter fibres allowed for greater interfacial slippage. These findings highlight the critical role of optimizing fibre geometry and volume fraction in tailoring biocomposite properties for specific engineering applications.

Keywords: Fibre Geometry, Grewia *optiva*, Mechanical Purification, Taguchi Method, Thermosetting matrix

Natural fibre-reinforced polymer composites have recently garnered more attention than synthetic alternatives due to pressing ecological and environmental concerns (Prasad *et al.,* 2024). Based on their high strength-to-weight ratio, these natural fibres have piqued the interest of the engineering community as sustainable reinforcing materials for polymer composites (Skosana *et al.,* 2025). Driven by their suitability for sophisticated fibrous applications including composite reinforcement, textiles, cellulose nanomaterials, activated or conductive carbon, and biomaterials interest in natural fibres has grown continuously. Consequently, researchers from both academia and industry are now actively exploring new natural fibre sources and innovative applications for these materials (Antony Jose *et al.,* 2025). The unique properties of natural fibres such as low density, low cost, recyclability, non-toxicity, and biodegradability make them superior to synthetic fibres in various environmental metrics (Islam *et al.,* 2022; Abdullahi *et al.,* 2024). The global market for biocomposites is predicted to grow at a CAGR of 11.2% between 2017 and 2023, reflecting this shift (Kapoor *et al.,* 2026). High strength, specific modulus, internal vibration damping, and wear resistance have further solidified the role of Fibre-Reinforced Polymer (FRP) materials in modern engineering (Rajak *et al.,* 2019). Key sources of natural fibres include bamboo, jute, hemp, flax, sisal, and ramie, all of which can significantly alter the physical, chemical, and tribological behaviors of a matrix (Nijjar *et al.,* 2022, Veeman *et al.,* 2024). The sustainability and accessibility of natural fibres have long attracted attention as reinforcing agents. These composites are more affordable, biodegradable, and less abrasive to processing equipment than their petroleum-based counterparts (Akter *et al.,* 2022, Puttegowda 2025). As eco-friendly materials, they are increasingly popular in product manufacturing for bicycles, electronics, and technical solutions (Agarwal *et al.,* 2020, Cenci *et al.,* 2022). The primary objective of this study is to promote biodegradable systems and reduce the environmental impact of synthetic polymers. Industries are increasingly replacing heavy conventional materials with lightweight FRP composites (Zaman *et al.,* 2013), these can be categorized into two groups: natural fibre-reinforced thermosetting polymers (immobile) and thermoplastic polymers (recyclable) (Chandrasekar *et al.,* 2021). Previous research by the author focused on lignocellulosic-based biocomposites, exploring surface modifications such as alkalization and cross-linking agents like glutaraldehyde (GLA) to improve interfacial bonding (Seyoum *et al.,* 2024, Kapoor *et al.,* 2025). Another study investigated pure glass, pure jute, and hybrid laminates, concluding that hybridization significantly improves mechanical properties. Recent trends also suggest using unconventional resources, such as cow dung fibres as viable reinforcements for automotive components (Sezgin *et al.,* 2017, Dias *et al.,* 2022). For this study, the retting process was used to extract fibres by breaking down pectin and gums.

MATERIALS AND METHODS

Material Fabrication and Characterization

The Grewia *optiva* Fibre

Grewia *Optiva* is a medium sized tree of typically 12-15 m height shown in Fig. 1 (a) which is abundantly available in the sub-Himalayan terrains where day temperatures vary from 2°C to 38°C and where summer and autumn months are dry. Kumar *et al.* (2021) reported that, the Grewia *Optiva* tree belongs to the Tiliaceae family. This name was given by one of the founders of plant Physiology after Nehemiah Grew (1964-1712). The bast fibres shown in Fig.1 (b) obtained from the Grewia *Optiva* tree is used for making ropes and different craft items by local farmers (Singh and Singh, 2018).

Fibre Extraction and Mechanical Purification

The reinforcement used in this study was derived from the bast of the Grewia *optiva* tree, a species native to the sub-Himalayan regions. The fibres were initially extracted using the traditional water-retting

(a) Grewia *optiva* tree **(b) Extracted Fibres**

Fig. 1: (a) Grewia *optiva* plant (b) Extracted fibres

Fig. 2: Chemical-free surface cleaning of Grewia *optiva* reinforcement *via* manual combing for enhanced interfacial bonding

Fig. 3: Cutting of raw Grewia *Optiva* Fibre

process to break down natural gums and pectins. A key novelty of this research involves a mechanical cleaning phase to enhance the raw fibre quality without chemical treatment as shown in Fig. 2. An iron strand brush was employed to vigorously comb the fibres, effectively removing residual surface impurities, waxes, and loose debris. This mechanical surface purification creates a cleaner topography for interlocking with the epoxy resin.

Precision Cutting and Uniformity

Following the purification process, the raw fibres were prepared for composite integration through systematic sizing. To investigate the effect of fibre geometry, the cleaned strands were cut into three distinct lengths: 5 mm, 10 mm, and 15 mm as shown in Fig. 3. This was achieved using high-precision industrial scissors to ensure strict uniformity and dimensional accuracy across all reinforcement samples. These standardized short fibres were then utilized to achieve isotropic mechanical qualities in the final fabricated specimens.

Density of Grewia *optiva* Fibre

The density of raw Grewia *optiva* fibre was measured using a pycnometer. For testing, reinforcing fibre samples were cut into 150 mm pieces and dried in an oven at 60°C for 4 hours to remove all moisture as shown in Fig. 4. The density was calculated using the formula given in Eq. 1 and calculation is given in the Table 1.

$$G(\text{specific gravity}) = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad \textbf{(Eq. 1)}$$

Now, $G = \frac{\rho_f}{\rho_w}$

Volume Fraction

The fibre volume fraction and matrix volume fraction are defined as the ratios of the fibre volume and matrix volume to the total volume of the composite, respectively. For the fabrication of the composite specimens, the epoxy resin and hardener were mixed in a prioritized volume ratio of 100:12, ensuring an optimal curing process and structural integrity. The total volume of the composite is determined by the sum of the constituent volumes, as expressed in Eq. (2):

$$V_c = V_f + V_m \quad \textbf{(Eq. 2)}$$

Where, V_c is the total volume of the composite; V_f is the volume of the reinforcing fibres; V_m is the volume of the polymer matrix

Consequently, the individual volume fractions (v_f and v_m) can be calculated as:

$$v_f = \frac{V_f}{V_c} \quad \text{and} \quad v_m = \frac{V_m}{V_c}$$

Fig. 4: Density finding using Pycnometer

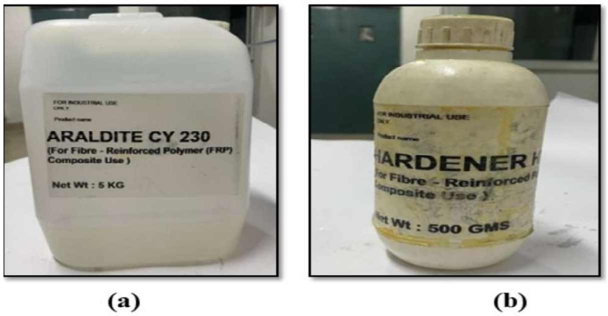
Table 1: Density of raw *Grewia optiva* Fibres

Parameter	Description	Measuring weight
M_1(g)	Mass of empty pycnometer	629.00
M_2 (g)	Mass of pycnometer + Fibre	634.5
M_3 (g)	Mass of pycnometer + Fibre + water	1513.04
M_4 (g)	Mass of pycnometer + water	1512
Mean Density (g/cm^3)	Calculated Fibre density	1.232
Std. Deviation (Ã)	Experimental Precision	±0.0026

The sum of these fractions must always equal unity (v_f+v_m=1), assuming a void-free fabrication process.

Composite Fabrication: Manual Hand Layup

The epoxy used in this study was Araldite CY 230-1**,** a Bisphenol-A-based thermosetting resin supplied by Excellence Resins, Meerut as shown in Fig. 5 (a) and this research was conducted in the Fracture Mechanics Lab, Department of Mechanical Engineering, College of Technology, and GBPUAT Pantnagar**.** It is a low-viscosity, unfilled epoxy resin that contains a small amount of plasticizer, which helps improve its flow and makes it easier to mix and spread during composites fabrication. This resin is known for its high stiffness, strong bonding with natural fibres and very low shrinkage during curing and good thermal and chemical stability**.** The hardener used was Aradur HY 951, an aliphatic amine-based curing agent also sourced from Excellence Resins, Meerut. It has a very low viscosity, which makes it easy to mix with the Araldite resin as shown in Fig. 5 (b). HY 951 helps the epoxy cure properly at room temperature and increases the toughness and strength of the final composite.



(a) (b)

Fig. 5: (a) Epoxy resin Araldite CY 230-1 (b) Aradur Hardener 951

The fabrication of the composite samples was performed using the manual compression hand layup method as shown in Fig. 6 (Al Mahmood *et al.,* 2017, Prasad *et al.,* 2019; Amar *et al.,* 2025). The specific fabrication steps were as follows:

- **Matrix Preparation:** The low-viscosity, plasticized epoxy resin was mixed with the aliphatic amine-based curing agent in a volume ratio of 100:12 to facilitate an effective room-temperature cure.
- **Reinforcement Loading:** Randomly oriented short fibres were distributed into the mold

Fig. 6: Step-wise Epoxy based Hand Lay-Up casting process

Table 2: Factor and its levels

S.No.	Factors	Level 1	Level 2	Level 3
1	Orientation	Random	Random	Random
2	Fibre length (mm)	5	10	15
3	Fibre volume (%)	20	30	40

Table 3: Design of Experiments for Mechanical and Physical Properties

Exp. No	Specimen Label	Ultimate Tensile Strength (MPa)	Flexural Strength (MPa)	Water Absorption Rate (%)
1	Neat Epoxy	44.34	105	1.24
2	GO (5 mm, 20%)	55.11	112.5	4.18
3	GO (5 mm, 30%)	62.00	119.8	6.75
4	GO (5 mm, 40%)	52.38	108.2	9.15
5	GO (10 mm, 20%)	58.94	115.4	4.38
6	GO (10 mm, 30%)	56.59	113.1	6.89
7	GO (10 mm, 40%)	48.42	106.3	9.38
8	GO (15 mm, 20%)	53.80	110.6	4.40
9	GO (15 mm, 30%)	49.63	107.8	7.05
10	GO (15 mm, 40%)	44.95	105.4	9.55

according to the Taguchi L9 design, utilizing volume fractions of 20%, 30%, and 40%.

- **Sample Curing:** The specimens were allowed to cure under manual compression to minimize void formation, ensuring the sum of the constituent volume fractions equals unity. The fabricated composites were left to cure for duration of 48 hours to ensure complete polymerization and structural stability.

Design of experiment (DOE)

Based on data from earlier studies, the composition of the fibre and epoxy resin combination was calculated as presented in Tables 2 and 3. This formulation followed a systematic statistical analysis using the Taguchi method to optimize the composite parameters. For this experimental investigation, the sample preparation included 9 flexural (ASTM D790) and 9 tensile specimens (ASTM D3039/ D3039M), each fabricated in accordance with ASTM standards. To ensure statistical reliability and minimize experimental error, each unique sample configuration was tested five times using a Universal Testing Machine of capacity 200kN under quasi-static conditions. Subsequently, the influence of these two primary factors i.e., fibre length and volume fraction each evaluated at three distinct levels was analyzed to determine their impact on the key quality characteristics of the biocomposites. The optimization was governed by specific Signal-to-Noise (S/N) ratio criteria to tailor the structural performance:

- **Larger-the-Better Approach**: This characteristic was applied to both Ultimate Tensile Strength and Flexural Strength, as the primary goal was to maximize the load-bearing capacity of the material.,
- **Smaller-the-Better Approach**: This characteristic was utilized for the Water Absorption Rate, as minimizing hydrophilic uptake is essential for maintaining the environmental stability and structural integrity of the composite.

This systematic approach allows for a comprehensive understanding of how varying reinforcement loading and dimensions affect the overall structural and physical performance of the *Grewia optiva* biocomposites.

RESULTS AND DISCUSSION

Ultimate Tensile Strength of Grewia *Optiva* Fibre-Reinforced Composite

The Ultimate Tensile Strength (UTS) of the untreated Grewia *optiva* (GO) reinforced epoxy composites demonstrates a clear reinforcement effect, with all fibre-loaded samples outperforming the neat epoxy baseline of 44.34 MPa as shown in Fig. 7. The maximum tensile strength was recorded at 62 MPa

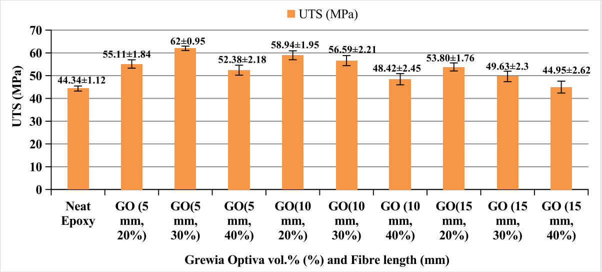


Fig. 7: Variation of UTS for different fibre length and loading in Grewia *optiva* Fibre Reinforced composite

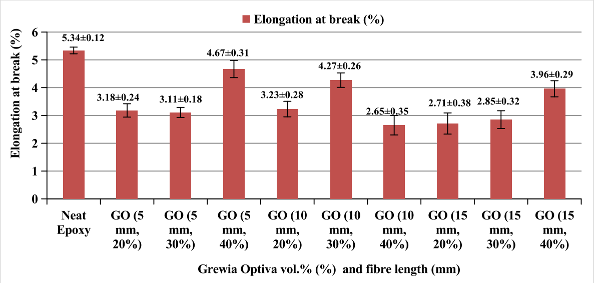


Fig. 8: Variation of elongation at break (%) for different fibre length in Grewia *Optiva* Fibre Reinforced Composite

for the configuration involving a 5 mm fibre length and 30% volume fraction, representing a significant improvement despite the absence of chemical surface modification. This enhancement indicates that the raw GO fibres possess inherent structural integrity sufficient to reinforce the epoxy matrix through mechanical interlocking. However, the performance is highly sensitive to fibre loading and length; a consistent decline in strength is observed as the volume fraction increases to 40% across all categories. Specifically, the 15 mm / 40% configuration dropped to 44.952 MPa, nearly matching the strength of the neat resin. The reduction in performance at higher loadings and longer lengths in these untreated specimens is likely due to the presence of natural oils, waxes, and hemicellulose on the fibre surfaces, which hinder the formation of a strong interfacial bond with the hydrophobic epoxy matrix. Consequently, while the untreated fibres provide an effective low-cost reinforcement at moderate loadings, the lack of surface purification limits the composite's ability to sustain higher fibre concentrations without significant loss in structural integrity.

Elongation at break of Grewia *optiva* Fibre Reinforced composite

The percentage elongation at break for the untreated Grewia *Optiva* (GO) reinforced epoxy composites reveals a significant reduction in ductility compared to the neat epoxy, which exhibited a maximum elongation of 5.34% as shown in Fig. 8. This trend is typical for fibre-reinforced polymers, as the introduction of relatively stiff natural fibres restricts the mobility of the polymer chains, leading to a more brittle materi*al.,* Interestingly, the highest elongation among the composites was observed at the 5 mm / 40% configuration (4.67%) and the 10 mm / 30% configuration (4.27%). These peaks suggest that at specific fibre densities and lengths, the fibres allow for a degree of micro-interfacial slippage or localized matrix deformation before final fracture occurs. Conversely, the lowest ductility was recorded at the 10 mm / 40% and 15 mm / 20% configurations, falling as low as 2.65%. The fluctuating nature of the elongation data in these specimens likely stems from inconsistent interfacial bonding; the presence of natural surface waxes and impurities prevents the fibres from fully integrating with the epoxy, causing premature failure at points of poor adhesion or fibre clumping. Overall, while the GO fibres enhance the strength of the composite, they simultaneously decrease the strain capacity, making the resulting biocomposite stiffer and more prone to brittle failure than the base resin.

Flexural Strength of Grewia *Optiva* Fibres Reinforced Composite

The flexural strength results for the untreated Grewia *Optiva* (GO) reinforced epoxy composites show a similar trend to the tensile performance, with all reinforced samples surpassing the neat epoxy baseline of 105 MPa as shown in Fig. 9. The maximum flexural strength of 119.8 MPa was achieved at a 5 mm fibre length and 30% volume fraction, indicating that this configuration provides the most effective resistance against bending loads. As the fibres are integrated into the matrix, they act as load-bearing elements that hinder crack propagation and enhance the overall stiffness of the composite. However, a noticeable decrease in flexural performance occurs as the fibre loading

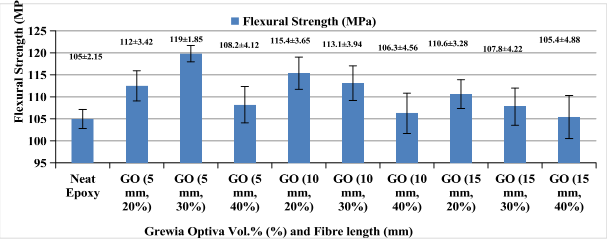


Fig. 9: **Variation of flexural strength of untreated Grewia *Optiva* Fibre Reinforced composite as a function of fibre length and fibre volume fraction**

reaches 40%, particularly in the 10 mm and 15 mm length categories. For instance, the 15 mm / 40% sample dropped to 105.4 MPa, nearly equivalent to the strength of the neat resin. This reduction in the untreated state is caused by the presence of natural impurities and waxes on the fibre surface, which prevent full resin infiltration. In bending tests, the lower surface of the specimen is under tension while the upper surface is under compression. Consequently, while the untreated GO fibres provide a substantial boost to the flexural modulus at moderate concentrations, their effectiveness is limited at higher loadings due to structural irregularities and weak fibre-matrix adhesion.

Water Absorption Rate of Grewia *Optiva* Fibre Reinforced composite

The water absorption behavior of the untreated Grewia *Optiva* (GO) reinforced epoxy composites highlights the significant impact of fibre loading on environmental stability. While the pure epoxy matrix exhibited high moisture resistance with a saturation point below 2%, all GO-reinforced composites showed a marked increase in uptake due to the hydrophilic nature of the natural fibres as shown in Fig. 10. The results indicate that as the fibre volume fraction increases from 20% to 40%, the water absorption rate rises substantially, with the 15 mm / 40% configuration reaching a peak near 10%. This behavior follows a Fickian diffusion pattern, where initial rapid volume gain eventually plateaus at saturation. In these untreated specimens, the presence of natural surface waxes and a weak interfacial bond create capillary pathways that facilitate moisture ingress. Consequently, while GO fibres provide reinforcement, higher loadings significantly increase susceptibility to moisture, especially with longer fibre lengths.

Statistical Analysis and Optimization

Ultimate Tensile Strength (Larger the better)

The experimental results were analyzed using Signal-to-Noise (S/N) ratios to identify the optimal parameters for maximizing mechanical performance as detailed in Table 3 using Minitab 2022 free version. According to the response analysis (Table 4), fibre Volume was identified as the most

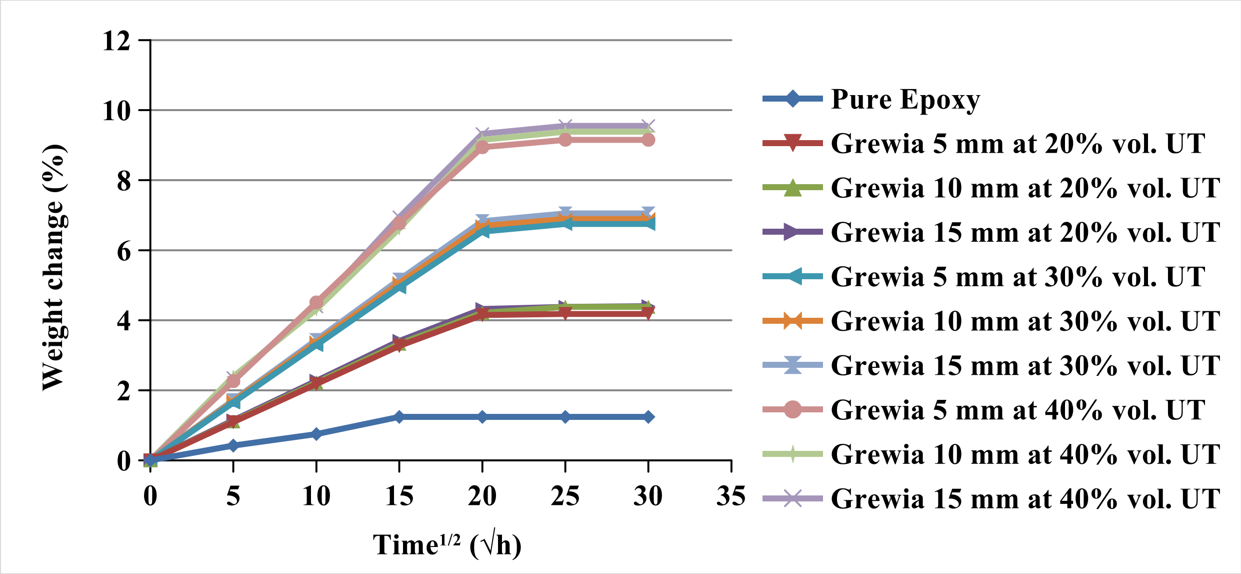


Fig. 10: Water absorption of Grewia *optiva* Fibre Reinforced composite

Table 3: L9 Orthogonal Array

Fibre length (mm)	Fibre volume (%)	Ultimate Tensile Strength (MPa)	Water absorption Rate (%)	SNRA1	MEAN1	SNRA2	MEAN2
5	20	55.11	4.18	36.9008	83.805	-12.4235	4.18
5	30	62	6.75	37.8275	90.9	-16.5861	6.75
5	40	52.38	9.15	36.4792	80.29	-19.2284	9.15
10	20	58.94	4.38	37.41183	87.17	-12.8295	4.38
10	30	56.59	6.89	37.09476	84.845	-16.7644	6.89
10	40	48.42	9.38	35.89198	77.36	-19.4441	9.38
15	20	53.8	4.4	36.70358	82.2	-12.8691	4.4
15	30	49.63	7.05	36.09031	78.715	-16.9638	7.05
15	40	44.95	9.55	35.33917	75.175	-19.6001	9.55

influential factor, holding a Rank of 1 with a Delta value of 1.1, followed closely by fibre Length (Rank 2). The Analysis of Variance (ANOVA) in Table 5 confirms this trend, showing that fibre Volume contributes significantly to the total variation, reflected by an R-sq value of 49.87%. While the P-value of 0.126 indicates that the factor's influence is notable within the experimental range, the model suggests that the composite's integrity is highly sensitive to the amount of fibre reinforcement integrated into the matrix.

The Main Effects and Interaction plots (Fig. 11 and Fig. 12) for SN ratios further clarify these relationships, revealing that a fibre length of 5mm (Level 1) combined with a Fibre Volume of 20% to 30% yields the highest S/N ratios. Specifically, the interaction plot highlights a peak performance at the 5mm/30% configuration, suggesting that shorter fibres are better distributed and reinforced by the matrix at moderate loading levels. Conversely, as fibre length increases to 15mm or volume reaches 40%, a sharp decline in the S/N ratio is observed. This downward trend is reinforced by the Interval Plot (Fig. 13), where the 95% Confidence Interval for 40% volume sits significantly lower than the other levels. This suggests that high fibre loading likely leads to poor interfacial bonding or increased void content, identifying 30% as the critical threshold for maintaining superior mechanical properties.

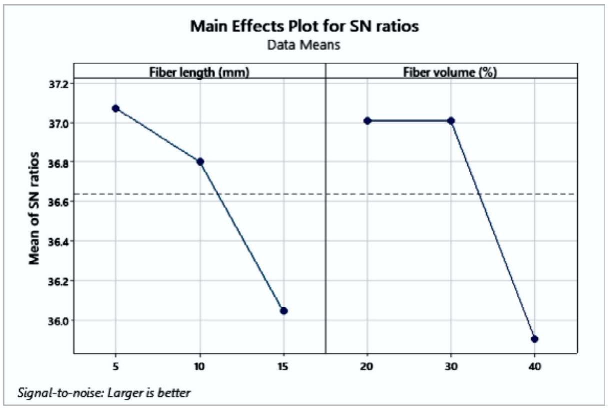


Fig. 11: Main effect plot for S/N ratio of UTS for different Fibre length and Fibre volume

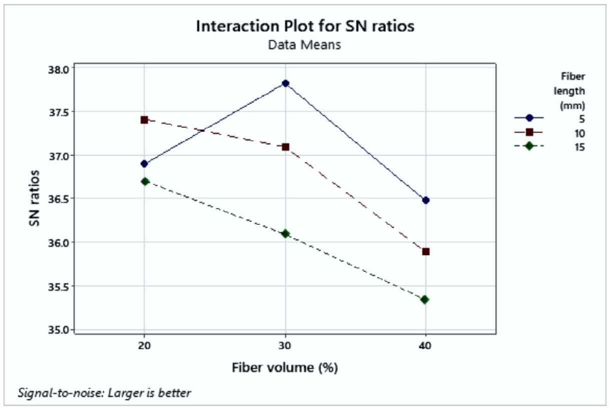


Fig. 12: Main Interaction plot for S/N ratio of UTS for different Fibre length and Fibre volume

Water Absorption Rate (Smaller the better)

The moisture sensitivity of the composites was evaluated using "smaller-the-better" Signal-to-Noise (S/N) ratios, where a higher S/N ratio represents a

Table 4: Response table for signal to noise ratios (larger the better) for Ultimate Tensile Strength

Level	Fibre length (mm)	Fibre volume (%)
1	37.07	37.01
2	36.8	37
3	36.04	35.9
Delta	1.02	1.1
Rank	2	1

Table 5: Analysis of Variance for SN Ratios

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fibre volume (%)	2	2.426	1.213	2.98	0.126
Error	6	2.438	0.4064		
Total	8	4.864			

S = 0.637507 R-sq =49.87% R-sq (adj) =33.16%

Table 6: Response table for signal to noise ratios (smaller the better) for Water Absorption Rate (%)

Level	Fibre length (mm)	Fibre volume %)
1	-16.08	-12.71
2	-16.35	-16.77
3	-16.48	-19.42
Delta	0.4	6.72
Rank	2	1

more desirable, lower water absorption rate. According to the response analysis in Table 5, fibre volume is the overwhelmingly dominant factor influencing moisture uptake, holding a Rank of 1 with a significant Delta value of 6.72, while fibre length has a negligible impact (Rank 2, Delta 0.4). This is further validated by the Analysis of Variance (ANOVA) in Table 6, which shows a P-value of 0.000 for fibre volume, confirming its high statistical significance. The exceptionally high R-sq value of 99.62% indicates that the moisture absorption behavior is almost entirely dictated by the fibre loading level, leaving very little variation to error or other parameters.

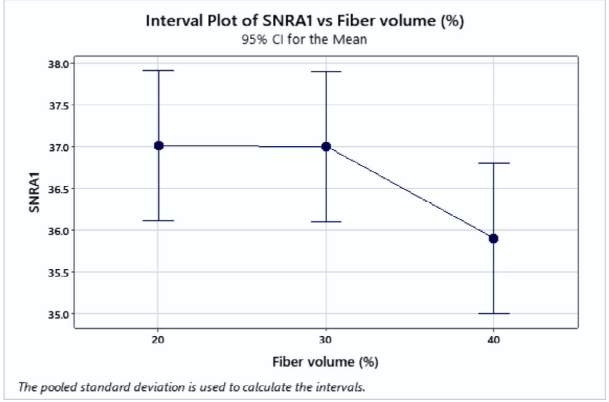


Fig. 13: Interval plot for S/N ratio of UTS for different Fibre length and Fibre volume

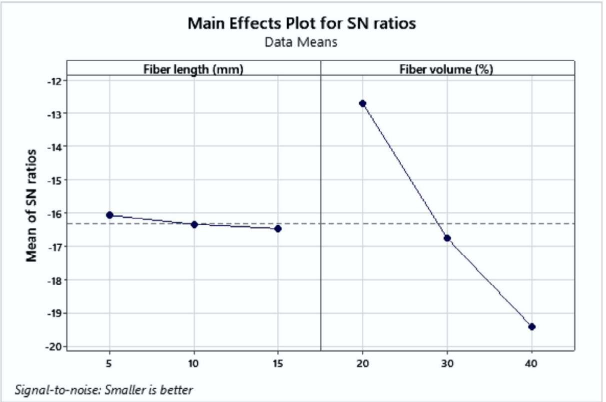


Fig. 14: Main effect plot for S/N ratio of Water Absorption Rate for different Fibre length and Fibre volume

The Main Effects Plot (Fig. 14) and Interaction Plot (Fig. 15) illustrate a sharp, linear decline in S/N ratios as fibre volume increases. The highest S/N ratio, representing the minimum water absorption, is achieved at Level 1 (20% fibre volume). As the volume fraction increases to 40%, the S/N ratio drops from -12.71 to -19.42, signaling a substantial increase in water uptake. This trend is consistent across all fibre lengths, as shown in the interaction plot (Fig. 15), where the lines for 5mm, 10mm, and 15mm run nearly parallel and close together. The Interval Plot (Fig. 16) emphasizes the precision of these results, showing tight 95% Confidence

Table 7: Analysis of Variance for SN Ratios of Water Absorption Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fibre volume (%)	2	68.6695	34.3348	784.26	0
Error	6	0.2627	0.0438		
Total	8	68.9322			

S = 0.209236 R-sq =99.62% R-sq (adj) =99.49%

Intervals that do not overlap between levels. This confirms that even small increases in fibre volume significantly degrade the composite's resistance to water, likely due to the hydrophilic nature of the natural fibres and the increased availability of hydroxyl groups for hydrogen bonding with water molecules.

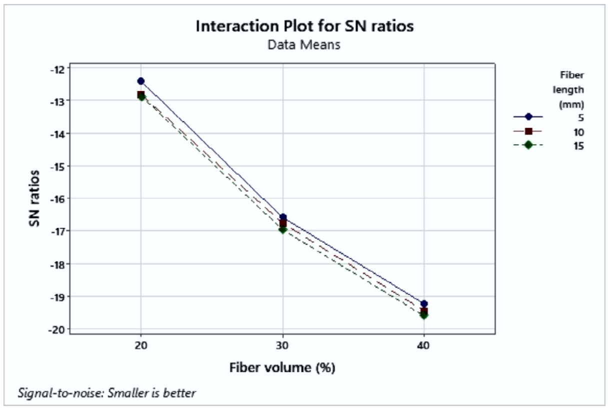


Fig. 15: Main Interaction plot for S/N ratio of Water Absorption Rate for different Fibre length and Fibre

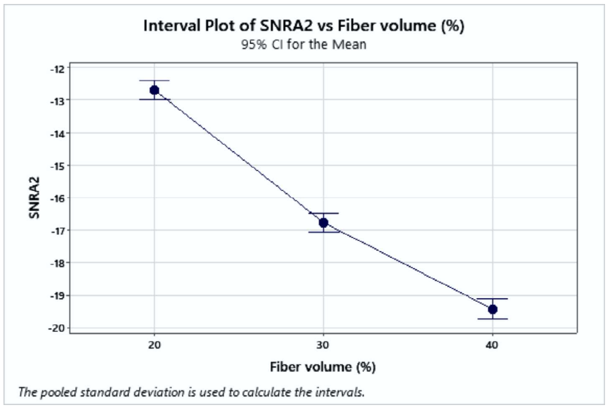


Fig. 16: Interval plot for S/N ratio of Water Absorption Rate for different Fibre length and Fibre volume

CONCLUSION

The experimental characterization of untreated Grewia *optiva* Fibre-Reinforced epoxy composites reveals that these natural fibres serve as an effective, sustainable alternative to synthetic reinforcements. The study successfully demonstrated that fibre geometry and loading concentrations are the primary determinants of the composite's overall performance. A core novelty of this research is the mechanical purification process, which involves using an iron strand brush to vigorously comb the fibres. This technique effectively strips away residual impurities, waxes, and surface dust without the need for chemical treatment, ensuring a cleaner topography for superior mechanical interlocking with the epoxy resin. The key performance findings are:

- **Mechanical Strength:** The optimal configuration for structural integrity was identified at a 5 mm fibre length and 30% fibre volume ratio, achieving a peak Ultimate Tensile Strength of 62 MPa and a Flexural Strength of 119.8 MPa.
- **Ductility and Strain:** The introduction of Grewia *optiva* fibres generally increased the brittleness of the material compared to neat epoxy. The maximum elongation at break (4.67%) was observed at the 5 mm/40% configuration, where shorter fibres allowed for greater micro-interfacial slippage.
- **Environmental Stability:** Water absorption is directly correlated with fibre content due to the hydrophilic nature of natural fibres. The minimum moisture uptake occurred at the 5 mm/ 20% loading, while the highest absorption (nearly 10%) was recorded at the 15 mm/40% configuration.
- **Statistical Significance:** ANOVA confirmed fibre volume as the most significant factor (P = 0.000 for water absorption), explaining over 99% of the variance in moisture uptake and approximately 50% of the variance in mechanical S/N ratios.
- **Predictive Optimization:** S/N ratio trends identified a negative correlation between fibre length and stability; while 30% volume is optimal for 5 mm fibres, the interaction plots indicate that any volume increase beyond 20% for 15 mm fibres causes linear performance degradation.

The results indicate that while untreated Grewia *optiva* fibres provide substantial reinforcement through mechanical interlocking, their performance is limited at higher loadings (40%) and longer lengths (15 mm). Consequently, for high-load engineering applications, a moderate fibre loading of 30% is recommended to ensure effective stress transfer while minimizing structural defects and moisture susceptibility.

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