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Research Article

Effect of Nano TiO_2 Filler Addition on Mechanical Properties of Bamboo/Polyester Hybrid Composites and Parameters Optimized Using Grey Taguchi Method

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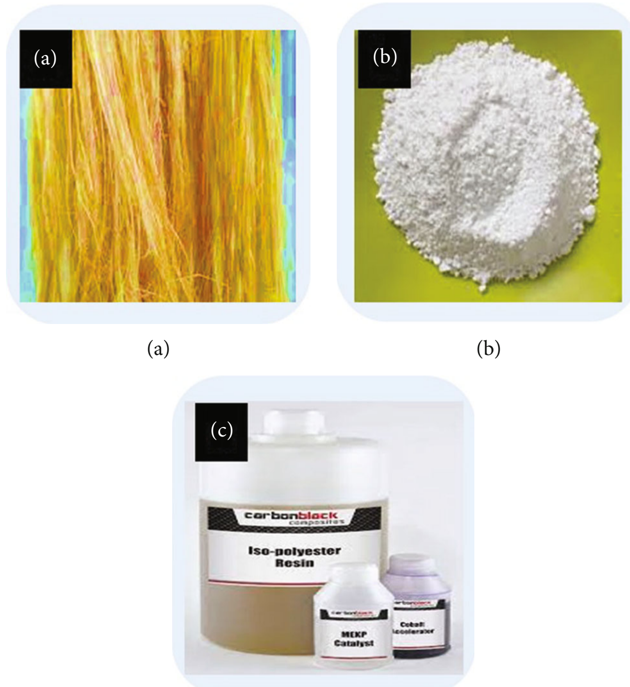
Exploration has shifted from traditional materials and alloys to composite materials in recent years to develop lightweight, high-effective materials for specific purposes. Natural fibres are less costly, biodegradable, and nonflammable than glass fibres. This study explores how titanium oxide affects woven polyester reinforced composite's mechanical and physical characteristics. Nanocomposites were created by hand utilizing the following terms: (i) TiO_2 nanoparticle filler weight ratio, (ii) fibre content, and (iii) fibre diameter, all at three unique levels. Using the L9 (3^3) orthogonal design, nine composite samples are generated and tested according to the ASTM standard. According to the research, hybrid composites containing 4% titanium oxide powder and 15 mm length of bamboo fibre with 0.24 mm of bamboo fibre diameter have high mechanical strength. Adding fibre to pristine polyester increased its mechanical properties. As the fibre and filler percentages grew, more effort was required to break the fragments between the matrix and its resin. The verification test, which uses the optimal processing value and grey relational analysis, outperforms the real test results by a wide margin. Tensile strength increased by 14.76%, flexural strength increased by 14.07%, and hardness increased by 25.55%.

1. Introduction

Biocomposites are quickly becoming one of the most intriguing study areas. Organic fibre-based composites have the greatest geographic market in Germany. Because of their ease of manufacture, increased productivity, and significant cost savings, polymers have essentially replaced conventional materials. To satisfy the high strength/modulus criteria, fillers and fibres can be utilized to change the characteristics of polymers [1]. Glass fibre reinforced composites have many applications. Still, their nonrecyclability is a disadvantage at the end of their useful life. Natural fibres provide unique properties to the completed composite, particularly those related to environmental protection, such as biodegradability, inexhaustibility of raw materials, and less aggressive and harmful behaviour [2]. Natural fibres offer various advantages as reinforcing in polymers, including nonabrasiveness, high biocompatibility, low power



(a) (b)

(c)

Figure 1: Photographic images of (a) bamboo reinforcement, (b) TiO_2 filler, and (c) polyester matrix materials.

Table 1: Mechanical properties of bamboo fibre and epoxy matrix.

Sl. no.	Properties	Bamboo fibre	Epoxy resin
1	Cellulose (%)	68.42-71.25	—
2	Hemicellulose (%)	25.10-32.47	—
3	Lignin (%)	17.25	—
4	Density (g/cm^3)	1.41	1.15
5	Tensile strength (MPa)	615-862	29.5-31.25
6	Young's modulus (GPa)	35-45	3.1
7	Elongation (%)	1.3-1.7	1.6

Table 2: Constrains and their stages for hybrid composite.

Sl. no.	Constraints	Symbols	Stages S1	S2	S3
1	TiO_2 powder (wt.%)	A	2	4	6
2	Bamboo fibre length (mm)	B	5	10	15
3	Bamboo fibre diameter (mm)	C	0.24	0.82	1.45

consumption, and low cost. Natural fibres are likewise low in density and have a high specific property [3]. Natural fibres offer mechanical properties comparable to traditional reinforcement. As a result, natural fibres' intrinsic properties can match global market expectations, notably in the weight-loss industry. As a result, they might be a suitable replacement for nonrenewable synthetic materials [4]. Due to their characteristics and quantity, wool, flax, jute, and silk are the most often utilized natural fibres in lightweight textiles. When utilized in composites, jute fibre provides several advantages. It possesses wood-like properties, for example, since it is a besets fibre [5].

Bamboo is among the world's toughest and fastest-growing plants. Bamboo forests occupy over 23 million hectares of the surface of the land. China contains one-third of the world's bamboo forest, making it the world's wealthiest country. Fast growth, sustainable use, high stiffness, ease of processing, and eco-friendliness are just a few benefits of using bamboo as a product [6]. People have continued to use and investigate bamboo for the last eight thousand years. For generations, bamboo has been the main source for China's weave, wood, newspaper, and fibre composite industries, providing plentiful and high-quality cellulose fibres. Bamboo hardwood, bamboo paper goods, bamboo fibre goods, bamboo ashes, bamboo acid, bamboo photography goods, bamboo extracts of the leaves, and other bamboo items are examples of traditional everyday needs and artisan articles [7]. Even though the bamboo sector employs bamboo to manufacture handicrafts, chairs, hardwood, reed hardwood composite, and other products, it fails to capitalize on the material's ecological and economic advantages. The existing bamboo industry's challenges are its low comprehensive usage of bamboo materials, very little automation, generates few high-value goods and lacks of scalability [8]. On the other hand, the hydrophilic nature of natural fibres is a significant drawback when employed as fibre materials. Low moisture friction in natural fibres causes incompatibilities and poor hydrophilicity with hydrophobic polymers, disrupting interactions at the fibre/matrix interface [9]. Chemical or physical alterations are widely utilized to offer polymeric matrixes bonding and adhesive affinities, as well as dimensional precision. Chemical surface

Table 3: L_9 orthogonal array of hybrid composites.

Trail no.	TiO_2 powder (wt.%) A	Bamboo fibre length (mm) B	Bamboo fibre diameter (mm) C
1	2	5	0.24
2	2	10	0.82
3	2	15	1.45
4	4	5	0.82
5	4	10	1.45
6	4	15	0.24
7	6	5	1.45
8	6	10	0.24
9	6	15	0.82

Table 4: Outcomes of current investigation.

Experiment no.	Tensile (MPa)	Flexural (MPa)	Hardness (BHN)
1	52.46	81.60	39.32
2	53.93	83.07	40.79
3	55.13	84.27	41.99
4	56.52	85.66	43.38
5	54.55	83.69	41.41
6	63.56	92.70	50.42
7	50.40	79.54	37.26
8	52.64	81.78	39.50
9	56.46	85.60	43.32

modification using bonding chemicals is often utilized to improve the interface and adhesion between the nonpolar matrix and the polar cellulosic fibres and optimize the latter's hydration for sustainability in polymer matrices [12]. Alkaline treatments, methylation, grafting copolymerization, and maleic-anhydride-polypropylene copolymer have all been shown to overcome incompatible interface polarity between natural fibre and polymer matrices [10, 11].

Several researchers have used hybridizations to enhance the mechanical characteristics of natural fibres. Hybrid composites mix two or more fillers in the same matrix. By reducing the shortcomings of a single composite, hybridization improves the mechanical performance of natural fibre reinforced plastic composites [13]. On the other hand, the effect of mixing fibres in matrices on boosting mechanical qualities has reached its limit. Even better, nanoparticles are employed to strengthen the bond between the matrix and the fibre, improving its characteristics. As a result, epoxy resins are increasingly incorporating nanoparticles. This study examines how nano powder may be utilized to regulate bio composites' behaviours. Nanoparticles have unique properties due to their nanometre scale, which may be used to create new goods or improve the efficacy of existing ones [14]. Nanoparticles are utilized for various applications, including water purification, energy generation, and pollution monitoring. Much of the research focuses on how innovative nanoparticles might be used to address important environmental issues. Titania (TiO_2) is a naturally occurring metal in amorphous and crystalline forms [15]. The crystalline and hematite forms are both tetrahedral, whereas anatase is extradural. Nanoparticles have special properties due to their nanometre size.

TiO_2 crystals, on the other hand, have distinct physicochemical properties due to their intrinsic electron configuration and crystalline structure [16]. Due to variations in physical properties, upgraded TiO_2 is more relevant than coarse TiO_2 for creating an antibacterial coating [17]. Biological applications include air and water filtering, colour removal, and focused sunlight splitting [18, 19]. Biomedical uses include photodynamic cancer therapy, medicine delivery systems for living cells, biosensing for biochemical tests, and peptidases in genetic modification. The photocatalytic capabilities of TiO_2 are the driving factor behind all of its applications [20]. Photogenerated electron pairs are generated when photoexcited with photons with energies greater than or equal to the energy band gap of TiO_2, resulting in the commencement of electrochemical processes at the TiO_2 surface and the formation of oxygen species. According to most research, this form of titanium oxide will help increase natural fibre adhesion to the polymeric matrix [21].

The grey-based Taguchi approach successfully handled several multiresponse challenges in the production process. Taguchi parameter design is a low-cost method of improving manufacturing processes and meeting high-quality targets without increasing expenses. The S/N ratio is used to assess the influence of noise components on the target characteristics. An orthogonal design of array (OA) is utilized to analyze a high number of variables in fewer tests. There are three performance criteria to evaluate the S/N ratio: short-the-better, larger-the-better, and nominal-the-better. Depending on the researched character, the S/N ratio condenses the various data points inside an experimental setting [22, 23].

The uniqueness of the present study is highlighted by the fact that this is one of the first studies to analyze composites employing weaved bamboo as reinforcement and nano TiO_2 as a filler material in epoxy resin under grey-based Taguchi optimization. The updated draught included this innovative idea. The main goals of this study are to create, test, and enhance the mechanical characteristics of hybridized bio composites using the parameters titanium oxide weight percent, bamboo fibre length, and bamboo fibre diameter. The TiO_2 filler-based composite materials were made using a simple hand lay-up procedure. Natural fibres were alkali-treated to improve adhesion and minimize moisture absorption, and their mechanical properties were examined and improved using Taguchi methodologies based on grey analysis. The results of this study are anticipated to expand the range of environments in which organic fibre-based composites may be used.

2. Materials and Methods

2.1. Materials. The Natural Fiber Industry in Vellore, Tamil Nadu, India, contributed the bamboo fibres. The bamboo

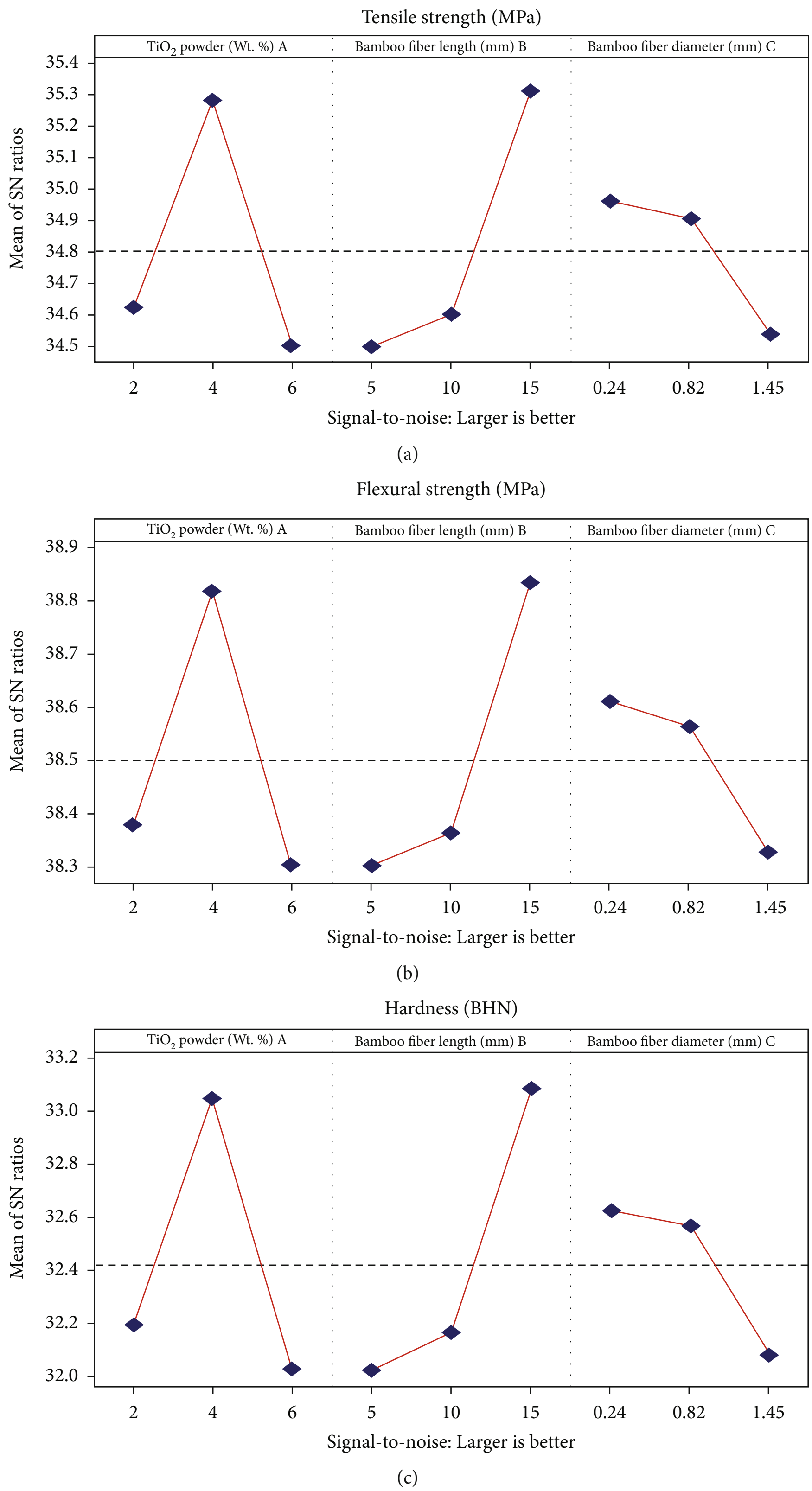


FIGURE 2: S/N ratio of mechanical properties of bamboo/TiO_2/polyester composites.

fibres were gently laved with clean water to remove the moisture and sundried for two days. The fibre was then submerged for four hours in a NaOH solution. Afterwards, the fibre was cleaned in clean water before being weaved at 75°C. In this investigation, titanium oxide and epoxy were used as a matrix. Naga Pharmaceutical Manufacturing provided the matrix and titanium oxide fillers in Chennai, Tamil Nadu, India. Figure 1 depicts the reinforcing, fillers,

Table 5: S/N and standardized S/N ratio.

Exp. no.	S/N ratio Tensile (MPa)	Flexural (MPa)	Hardness (BHN)	Standardized S/N Tensile (MPa)	Flexural (MPa)	Hardness (BHN)
1	34.397	38.234	31.892	0.172	0.167	0.179
2	34.637	38.389	32.211	0.292	0.283	0.300
3	34.828	38.513	32.463	0.386	0.377	0.397
4	35.044	38.656	32.746	0.494	0.484	0.505
5	34.736	38.453	32.342	0.341	0.332	0.350
6	36.064	39.342	34.052	1.000	1.000	1.004
7	34.049	38.012	31.425	0.000	0.000	0.000
8	34.426	38.253	31.932	0.187	0.181	0.194
9	35.035	38.649	32.734	0.489	0.479	0.500

Table 6: GRC and GRG of the composites.

Trail series	GRC Tensile (MPa)	Flexural (MPa)	Hardness (BHN)	GRG
Trail 1	0.377	0.375	0.378	0.377
Trail 2	0.414	0.411	0.417	0.414
Trail 3	0.449	0.445	0.453	0.449
Trail 4	0.497	0.492	0.502	0.497
Trail 5	0.431	0.428	0.435	0.431
Trail 6	1.000	0.999	1.008	1.002
Trail 7	0.333	0.333	0.333	0.333
Trail 8	0.381	0.379	0.383	0.381
Trail 9	0.495	0.490	0.500	0.495

Table 7: Response table for GRG.

Levels	TiO_2 powder (wt.%) A	Bamboo fibre length (mm) B	Bamboo fibre diameter (mm) C
L1	0.413	0.402	0.587
L2	0.644	0.409	0.469
L3	0.403	0.649	0.405

and matrix used in the research. Table 1 shows the mechanical properties of reinforcement and matrix.

2.2. Fabrication of Hybrid Composites. First, a stainless-steel mould measuring $150 \times 150 \times 3$ mm was refined. The polyester matrix was thoroughly blended with the appropriate amount of hardener and accelerator (10 : 1). Hand lay-up was used to create the titanium oxide powder and bamboo fibre composite. By hand stirring with a glass rod, various weight % of titanium oxide powder was dispersed in the produced epoxy resin. The matrix mixture was dispersed across the mould's fibre layers. The mould was adhered and cured outdoors for one day after the fibre mats were fully soaked with matrix combinations. The L_9 orthogonal array was chosen according to Taguchi's design for three constraints, each having three phases, and nine composite plates were built for future research. Desiccators were used to keep the hybrid composite samples from collecting any additional moisture. Tables 2 and 3 show the parameters, their ranges, and Taguchi's orthogonal arrangement (OA).

3. Methods and Testing

3.1. Characterization of Nanocomposite. The fabricated composite specimens were cut rendering to ASTM standard of D 638-03 replicas with a dimension of $150 \times 15 \times 3$ mm for tensile testing, ASTM D-790 (width 10 mm, length 125 mm, and thickness 3 mm) for flexural testing, and ASTM E-10 (width 20 mm, length 20 mm, and thickness 3 mm) for hardness testing.

3.2. Experimental Consequences by GRG Technique. The Taguchi experimental process approach is a helpful strategy for logical explanation, investigation, and optimization of various process parameters to obtain the intended outcome. The current investigation's experimental results are shown in Table 4 [24]. The primary restrictions are discovered by converting the research results into a S/N ratio. The S/N ratio features were divided into three phases based on the conclusive rationale for improving the principal feature: (i) greater is better, (ii) nominally better, and (iii) smallest is best.

3.2.1. Signals-to-Noise Ratio. The bigger the performance feature, regardless of the performing feature group, the higher the S/N ratio. Figure 2 shows the S/N ratio of mechanical properties of bamboo/TiO_2/polyester composites. As a result, the S/N ratio of the parameter's optimal level is the highest. The larger concept was used to analyze hardness, compressive, and impact strengths throughout the composites testing. As a result, prominent attributes' S/N ratios (larger is better) are represented as [23].

$$\frac{S}{N}\,\text{Ratio} = -10\ \log_{10} \frac{1}{e} \sum_{a=i}^{e} \frac{1}{X_{ab}^{2}}. \tag{1}$$

3.2.2. Normalized Signal-to-Noise Ratio. Normalization is a statistical input alteration that distributes the data uniformly and measures them into a proper assortment for further

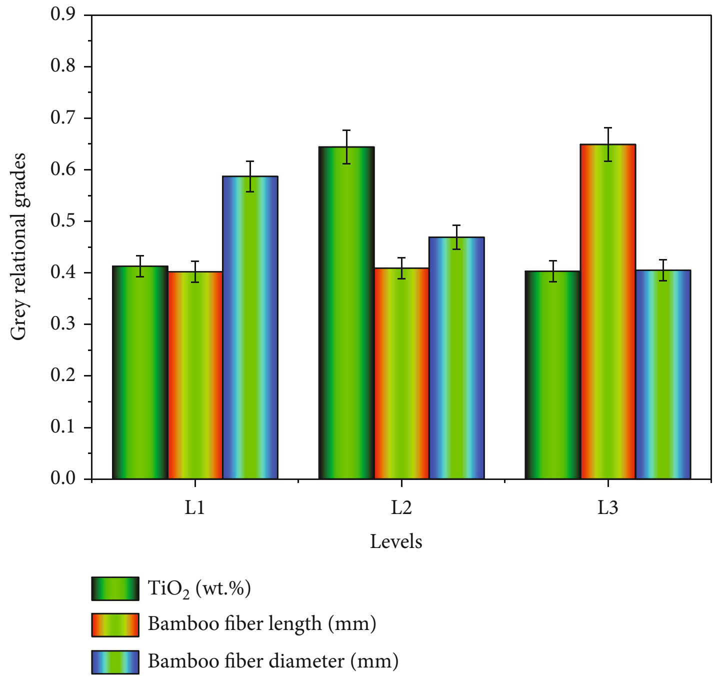


Figure 3: Grey relational grade values of bamboo/TiO_2/polyester-based nanocomposites.

Table 8: ANOVA of GRG.

Features	Constraints	DOF	SOS	MSOS	% of contributions
A	TiO_2 powder (wt.%) A	2	0.03718	0.0186	39.65
B	Bamboo fibre length (mm) B	2	0.03955	0.0198	42.18
C	Bamboo fibre diameter (mm) C	2	0.01704	0.0085	18.17
Error	—	0	—	—	—
Total	—	6	0.09377	—	100

Table 9: Comparison of initial and optimal parameters.

Response	Initial parameter	Optimal parameter	% of improvement
Levels	A2, B2, C3	A2, B3, C1	%
Tensile	63.25	74.21	14.76
Flexural	85.21	99.17	14.07
Hardness	40.12	53.89	25.55

inquiry. Zab is standardized as K_{ij} $(0 \leq K_{ij} \leq 1)$, utilizing equations to determine the right conclusion of assumptions for various components and eliminate discrepancies (Equation (2)). The hardest, compressive, and impact strengths were considered the most relevant parts of this investigation. The S/N ratio and standardized S/N ratio are well suited for the following aspects. Table 5 shows the result S/N and normalized S/N ratios [25].

$$K_{ij} = \frac{z_{ab} - \min\left(z_{ab} a = 1, 2, \cdots, e\right)}{\max\left(z_{ab} a = 1, 2, \cdots, k\right) - \min\left(z_{ab} a = 1, 2, \cdots, e\right)} \quad (2)$$

3.2.3. Grey Relational Grades (GRG). Equation (3) is used to convert each answer of the GRC into a GRG. The grey relational grading determines the best amount for each controllable component. Table 5 displays the results of the GRG.

$$\bar{\gamma_J} = \frac{1}{k}\sum_{i=1}^{m} \gamma_{ij} \quad (3)$$

where γ is the GRG of the jth trial and k is the sum of performance features. Later, for all L_9 (3^3) trails, the GRC and GRG were conducted. The multiresponse optimization challenge was reduced to a single-response optimal solution by combining Taguchi methods and grey relational analysis. The total GRG generated using the grey-based Taguchi approach is the single-performance feature. You may get the best overall grey relationship grade by looking for a parameter configuration. The GRC and GRG for nine trials are shown in Table 6.

4. Result and Discussion

4.1. Grey Relational Grades. The Taguchi technique and grey relation study were utilized to determine the optimal

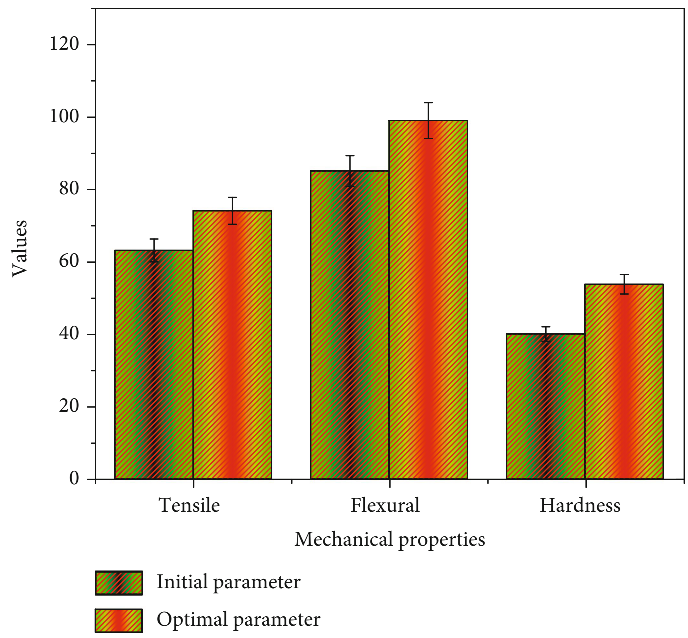


Figure 4: Comparison of initial and optimal parameters of mechanical properties.

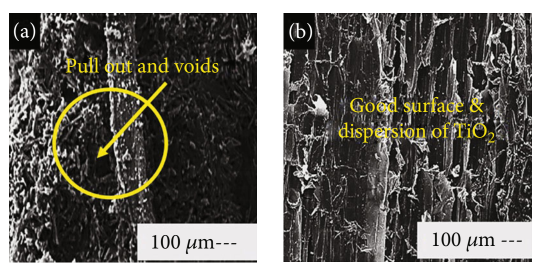


Figure 5: Microstructural image of (a) initial parameter and (b) optimal parameter specimens.

parameters for the mechanical characteristics of hybrid polyester composites. The best constriction groups and the most important characteristic in natural composites were lowered using grey-based testing and ANOVA. The average GRG for each constriction level was calculated using the Taguchi method's retort table. To calculate the grey relation score for titanium oxide powder, add the relation values of the grey relation coefficients of flat (level) 1 in column A (i.e., trials 1-3), then the relation values of flat 2 in the same column.

Trials 4-6 average the flat three relational values from the same column A, and trials 4-6 average the flat three relational values from the same column A (trials 7-9). Similarly, the bamboo fibre length and diameter will be selected with precision flatness. Table 7 illustrates this. Figure 3 demonstrates the GRG's reaction facts at various degrees of the composite's limits. According to statistics, the highest grey relation grade gives the best process constraint level [26, 27].

The usage of nano titanium will boost composite strength dramatically. Levels A2, B3, and C1 have the greatest grey relative grade value for titanium oxide powder weight, bamboo fibre length, and fibre diameter. The 4% titanium powder and 15 mm bamboo fibre with 0.24 mm diameter were optimal for hybrid composites. By increasing the quantity and size of holes in the polymer matrix, more filled titanium oxide impacted the decohesion bonding between the fibre and the matrix [28, 29]. The matrix and fibre connection get weaker as the titanium oxide weight ratio rises. This might be caused to titanium oxide acclamations in the matrix [30].

Fibre content, fibre direction, fibre diffusion, fibre composition, fibre-matrix bond strength, binding and wettability, originate, electrostatic interaction, complex formation, physical interfacial, and fibre length are all factors that influence the mechanical properties of natural fibre polymer composites [31, 32]. Fibre length is an important consideration when making fibre-reinforced polymeric materials. When fibres are overly long, they are entangled, producing dispersal issues. However, if the fibre length is too short, there is not enough stress transmission from the matrices to the fibre. Fibre breaking in fibre reinforced composites is mostly determined by the composite's kind and initial aspect ratio. Several scholars investigated the impact and significance of fibre length on the characteristics of fibre reinforced polymer composites. Increases in fibre length from 5 mm to 10 mm and 15 mm improved this research's

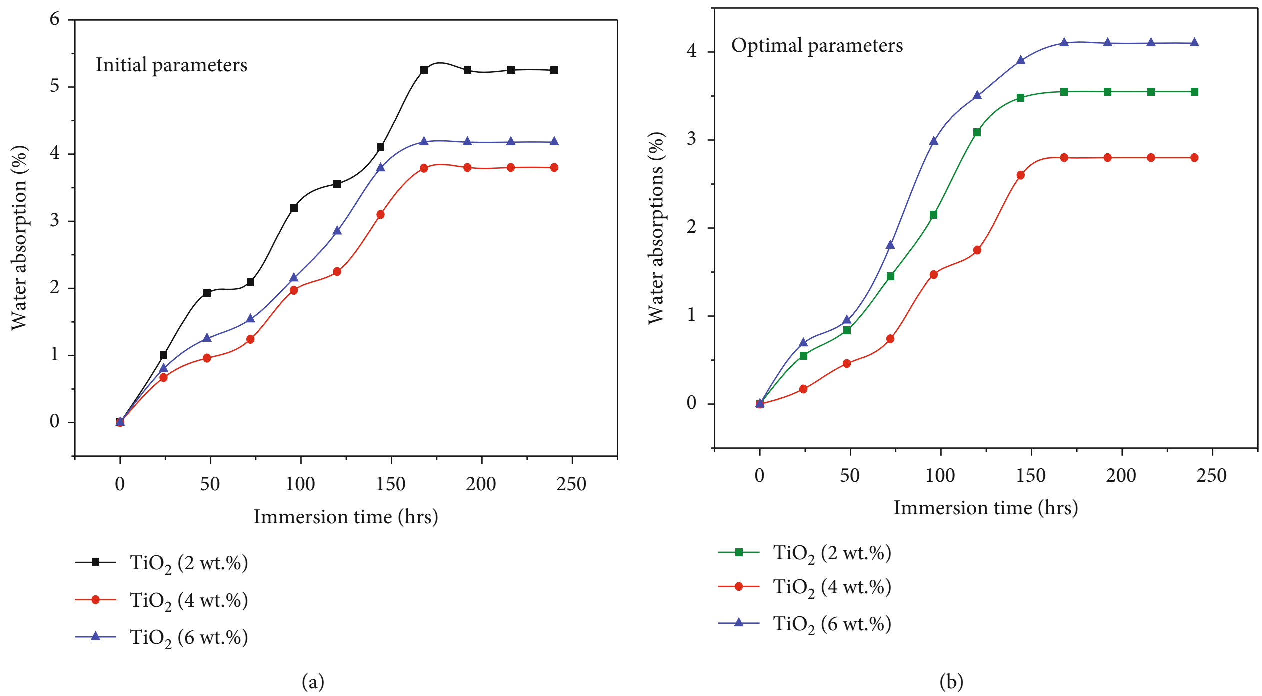


Figure 6: Water absorption behaviour of (a) initial parameter and (b) optimal parameter-based nanocomposites.

mechanical characteristics of nanocomposites. Composites with 15 mm fibre lengths have greater mechanical qualities than composites with 5 mm fibre lengths [33].

Generally, using fibres with a smaller radius or finer quality improves the characteristics of natural fibre reinforced polymer composites [34]. In comparison to fibre diameter, fibre length and fibre content significantly impact the mechanical characteristics of the nanocomposite, as shown in Figure 3. The following factors contribute to enhanced composite qualities when fibre diameter is reduced, or fineness is increased: (i) improved infrastructure facility and (ii) better surface-to-volume ratios, resulting in greater contact area among fibre and polymer matrices [33, 35]. The diameter is also significant since fibre diameters [36] greater than a specified value result in nanocomposite with lower strength [37]. Consequently, polymeric materials reinforced with fibres of larger diameters will have lesser performance. Flax fibres have a smaller diameter and finer texture than hemp and kenaf [38]. Hemp fibre-polypropylene composite and kenaf fibre-polypropylene composite have lower strength than flax fibre reinforced propylene composite [39].

4.2. ANOVA Analysis. The ANOVA results are utilized to determine which process parameters influence the impacting process variables in titanium oxide and bamboo-based hybrid composites [40]. In the ANOVA, the traditional GRG value can be utilized. The influence of modifying processing parameters on concert qualities may be determined using the percentage contribution obtained from the total sum of squared deviations [41].

In Table 8, ANOVA results show each process parameter's impact, with titanium oxide powder, bamboo fibre length, and bamboo fibre diameter accounting for 39.65%, 42.18%, and 18.17%, respectively [42]. This suggests that fibre length and nanoparticle inclusions are important in the current research.

4.3. Confirmation Test. A confirmation experiment is carried out to guarantee that the overall performance of nanocomposites has improved. Table 9 shows the final result for initial control factor values such as 4% titanium oxide powder weight, 10 mm of bamboo length, and 1.45 mm of fibre diameter (A2, B2, and C3) [43]. The following are the optimal process parameters as determined by a confirmation test.

The weight % of titanium oxide powder is 4%, the fibre length is 15 mm, and the bamboo fibre diameter is 0.24. (A2, B3, and C1). Table 8 demonstrates that the optimal parameters are preferable to the initial values in terms of percentage increase. Furthermore, the confirmation test results using the optimal process value and grey relation analysis are significantly superior to the real test data for tensile strength [44], flexural strength, and hardness strength. Tensile strength is up 14.76%, flexural strength is up 14.07%, and hardness is up 25.55% [45]. This is plainly shown in Figure 4. Figures 5(a) and 5(b) show the morphological characteristics of the initial and optimal specimens after tensile testing. It indicates the bonding strength using fibre pull-out [46]. The pull-out rage is higher for initial parameter specimens than optimal specimens [47].

4.4. Moisture Absorption Behaviour. Figures 6(a) and 6(b) demonstrate the proportion of water captured by bamboo/nano titanium-based polyester composites (b). The Indian's concern with water has changed dramatically over time.

Fibre reinforcement generally induces high moisture retention in polymer composites [48]. Initial parameter (A2, B2, and C3)-based composites had a high moisture content, but optimum parameter-based composite materials had a low relative humidity (A2, B3, and C1). According to the mechanical-fractured sample analysis, the ideal composite showed good fibre-to-matrix bonding capabilities [49]. This primarily resulted in the development of good water repellent properties. The polymer matrix is securely wrapped around the fibre due to excellent bonding, preventing water elements from reaching the exterior [50]. Due to the inadequate link between the matrix and fibre in the early parameter composites, water molecules may easily access the fibre surface. The composite's water absorption was improved as a result of this. After 144 hours of incubation, the initial and optimum parameter composites attained saturation.

5. Conclusion

The Taguchi approach and GRA were used to optimize the process constraints in this work, which looked at the mechanical properties of titanium oxide and bamboo-based polyester hybrid composites.

(a) The following conclusions were reached: These are the controlled process conditions proposed for titanium oxide and bamboo-based hybrid composites. Combining multiple components results in hybrid composites with improved mechanical properties

(b) According to statistical analysis (ANOVA), the length of bamboo fibre was the most important parameter, accounting for 42.18% of the total, followed by nano TiO_2 at 39.65% and fibre diameter at 18.17%

(c) The increased length of bamboo fibre provides better interfacial adhesion between the matrix and reinforcement. This will help to increase the stress transfer from matrix to reinforcement

(d) The grey relation analysis confirms the excellent process value, which is substantially better than the actual test data. Tensile strength has increased by 14.76%, flexural strength has increased by 14.07%, and hardness has increased by 25.55%

The study covered in-depth experimental research on bamboo and nano TiO_2 mechanical characteristics optimization. However, it is acknowledged that the fabrication of natural composites with nanofillers involves several difficulties and affects the calibre and characteristics of the materials. It is advised to select and optimize the processing parameters to produce a high-quality product with better-specialized qualities. The production and evaluation of a few matrix materials based on natural fibres and nanofillers are still areas where research might be done. By using appropriate techniques, it is possible to prevent the matrix from aggregating when new fillers are added. This will strongly impact the physic-mechanical characteristics of the composite that has been created.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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