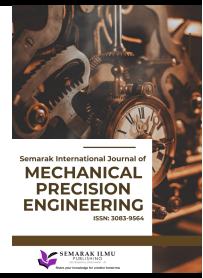




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Multi-Objective Optimization of Bamboo-Filled Plastic Gears in Injection Moulding using Hybrid Optimization

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ABSTRACT

The growing demand for lightweight and eco-friendly components has led to increasing interest in replacing conventional metallic and glass-fiber-reinforced gears with sustainable plastic alternatives. However, injection-moulded plastic gears often suffer from poor dimensional stability, shrinkage, and insufficient mechanical strength, limiting their use in high-performance applications. To address these challenges, this research investigates the potential of using bamboo fillers as natural reinforcement in polypropylene-based plastic gears and optimizes the injection moulding process parameters to enhance product quality. A hybrid optimization framework integrating the Taguchi method, Grey Relational Analysis (GRA), and Principal Component Analysis (PCA) was employed to achieve multi-objective optimization targeting minimal shrinkage and maximal tensile strength. The results demonstrated that incorporating bamboo fillers significantly improved mechanical properties while maintaining acceptable processability. Although the inclusion of bamboo filler enhanced dimensional stability and stiffness, it also led to a moderate reduction in tensile strength at higher filler loadings due to weak interfacial bonding, indicating a trade-off between mechanical strength and sustainability benefits. The optimized processing conditions obtained from the hybrid approach yielded superior dimensional accuracy and strength compared to unoptimized settings. Overall, this study establishes bamboo as a promising sustainable filler material and demonstrates the effectiveness of hybrid optimization in improving the performance of injection-moulded plastic gears.

1. Introduction

Gears are vital components in mechanical power and motion transmission systems, serving in applications ranging from automotive and household appliances to industrial machinery. Traditionally, metallic gears made of steel, brass, or bronze have dominated due to their superior

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strength and durability. However, the increasing demand for lightweight, cost-effective, and corrosion-resistant alternatives has accelerated the shift toward plastic gears. Plastic materials such as polypropylene (PP), nylon, and polyacetal offer several advantages, including low density, self-lubricating properties, noise reduction, and ease of mass production through injection moulding. Matkovič and Kalin [1] for example, discuss the effectiveness of polyamides and polyacetals, noting their lightweight nature and ease of manufacture, which contribute to design flexibility and a decrease in overall system weight and cost. Jain and Patil [2] emphasize the performance characteristics of various polymer materials that meet contemporary engineering expectations, particularly the needs of industries that prioritize lightweight construction and reduced production costs.

Although plastic gears offer numerous advantages, their performance remains limited under high loads and elevated temperatures. Studies have demonstrated that polymers used in gear applications often encounter issues related to dimensional stability and wear resistance when subjected to high-stress conditions. For instance, it has been reported that conventional PP or nylon gears generally have linear shrinkage values ranging from 1.0% to 2.5%, while metallic gears generally have lower shrinkage values of less than 0.3% [3]. The implications of such discrepancies extend to their tensile strength; nylon gears typically exhibit a tensile strength in the range of 25-50 MPa, significantly lower than that of steel gears, which exceed 500 MPa, or glass-fiber composites, which range from 80 to 120 MPa [4]. This disparity fundamentally restricts the performance of polymer gears in high-load conditions and exposes them to risks under thermal cycling environments, thereby raising concerns about their durability and reliability in critical applications. According to Singh *et al.*, [5], the operating speed plays a crucial role in determining the wear rate of polymer gears, as increased loads intensify surface degradation, emphasizing the need for better material selection and design improvements. Similarly, Kumar *et al.*, [6] revealed that temperature variations can further accelerate wear in Nylon gears, highlighting the strong interplay between mechanical performance and environmental factors. The durability and operational reliability of plastic gears under dynamic loading have also been examined by Sun *et al.*, [7], who reported that inadequate wear mitigation may result in severe failures within gear transmission systems. Supporting this view, Dong *et al.*, [8] identified wear and fatigue as dominant failure mechanisms, reinforcing the complexity of ensuring long service life for plastic gears in demanding operational environments.

To overcome these drawbacks, reinforcement of plastic matrices with fillers has become an effective approach to improving mechanical strength and thermal stability. Historically, the reinforcement of plastics has relied heavily on synthetic materials such as glass and carbon fibers. These fillers have proven effective at enhancing mechanical strength and thermal stability, but their non-biodegradability poses significant environmental challenges [9]. The need for sustainable materials has prompted the exploration of natural fibers, which not only mitigate ecological concerns but also leverage the advantageous properties of biomaterials. Among these, bamboo fibers are gaining attention for their remarkable properties, including a high strength-to-weight ratio, cost-effectiveness, and significant availability in many regions [10]. Bamboo has increasingly been recognized as a notable reinforcement material in composite applications due to its exceptional properties compared to other natural fibers like kenaf, jute, and sisal. Its cellulose content ranges from approximately 40% to 50%, which is comparable but generally lower than that of jute and sisal, which can reach up to 60% for jute [11]. However, the specific properties of different bamboo species can vary significantly, which influences their mechanical performance. Bamboo's tensile strength can reach values around 400 MPa, depending on the species and treatment methods [12]. Research has shown that incorporating bamboo fibers into polymer composites can significantly enhance their mechanical performance, resulting in notable increases in tensile strength and impact resistance. For

instance, bamboo fibers possess a higher Young's modulus compared to coir fibers, which indicates superior stiffness and load-bearing capacity, although comparisons with jute can be nuanced depending on the specific types studied [12]. Ochi [13] demonstrated the successful fabrication of bamboo-based spur gears capable of withstanding substantial loads while exhibiting performance comparable to conventional materials such as polyoxymethylene (POM). Similarly, the dynamic behavior of bamboo gears reported by Shi et al., [14] indicates their suitability for mechanical systems that demand lightweight and environmentally friendly components. Further, Nakaya *et al.*, [15] analyzed the tooth meshing characteristics of bamboo fiber bevel gears, emphasizing bamboo's potential as a sustainable alternative for advanced gear technologies without the environmental concerns linked to synthetic reinforcements. Another dimension of bamboo's utility is its ecological benefits alongside its strong mechanical performance. As a rapidly growing resource, bamboo is highly sustainable, leading to lower carbon emissions compared to conventional timber sources [16-17]. The implications of bamboo's growth rate contribute to enhanced biomass production for energy and material applications [18]. Bamboo forests can play a role in significant carbon sequestration, which is crucial for combating climate change [19].

Although several studies have explored the use of bamboo as a reinforcing material in plastic gear applications, research that combines bamboo filler integration with the optimization of injection moulding parameters remains scarce and underdeveloped. Injection moulding plays a crucial role in producing precision components across multiple industries, particularly for high-performance products such as plastic gears. The final quality of injection-moulded parts depends heavily on process parameter including melt temperature, injection pressure, cooling time, and injection speed where improper configurations can result in shrinkage, warpage, and reduced mechanical performance [20-22]. Hence, systematic optimization of these parameters is essential to achieve an optimal balance between dimensional accuracy and mechanical strength.

Among the various optimization techniques, the Taguchi method is increasingly recognized as an effective optimization technique in manufacturing, particularly for its ability to enhance process quality by minimizing variation and identifying significant parameters with fewer experimental trials. Its systematic approach not only improves product quality but also reduces the need for extensive and costly experimental setups, making it an appealing option for various applications in injection molding and polymer processing [23]. For instance, He and Wu [24] utilized this method to identify critical factors such as melt temperature and packing pressure in the injection molding of small-module plastic gears, resulting in significant improvements in dimensional precision, which underscores the method's relevance in precision manufacturing contexts. This is supported by Lee *et al.*, [25], who also employed the Taguchi method alongside analysis of variance and response surface methodology to assess injection molding parameters for plastic gear rack production, facilitating quicker mold designs and improved quality through simulation. Additionally, Tsai *et al.*, [26] demonstrated the utility of the Taguchi method in optimizing multi-cavity mold systems, achieving enhanced dimensional uniformity across parts by strategically tuning parameters associated with cavity filling. This confirmed the method's efficacy in minimizing discrepancies during manufacturing and offered cost-saving advantages by requiring fewer experimental runs. The integration of process design methods, such as Taguchi, with advanced data analytics, provides a modern approach to validation in complex injection mold designs, improving precision and reliability in manufacturing processes [27].

However, despite its proven effectiveness, the Taguchi method has inherent limitations when dealing with multi objective optimization problems, as it primarily focuses on optimizing a single response variable at a time. In complex manufacturing processes such as the injection moulding of bamboo filled plastic gears, multiple quality characteristics including shrinkage, tensile strength, and

wear resistance must be optimized simultaneously. Taguchi's single response framework may not adequately capture the interdependence and tradeoffs among these performance factors, leading to incomplete optimization outcomes. To overcome this limitation, the present research adopts a hybrid optimization approach that integrates the Taguchi method, Grey Relational Analysis (GRA), and Principal Component Analysis (PCA) to achieve multi objective optimization of the injection moulding process for bamboo filled polypropylene gears. This hybrid framework allows simultaneous evaluation of multiple performance indicators such as dimensional stability and mechanical strength, while systematically identifying the most influential processing parameters. The research gap lies in the limited studies that combine natural fiber reinforcement with systematic process optimization in plastic gear manufacturing, particularly using bamboo as filler in injection moulded PP components. The significance of this study is its potential to provide an ecofriendly and cost-effective alternative to conventional glass or carbon fiber composites while improving product performance through scientific process optimization. Therefore, the objective of this research is to develop and optimize the injection moulding process parameters for bamboo reinforced polypropylene gears using the Taguchi GRA PCA hybrid optimization method, with the goal of enhancing both mechanical and dimensional properties of the resulting composite gears. The outcomes are expected to contribute to both material innovation and process optimization in the growing field of green polymer engineering.

2. Methodology

2.1 Material Preparation

2.1.1 Polypropylene (PP)

Commercial-grade PP with a density of 0.91 g/cm³ and a melt flow index (MFI) of 10.78 g/10 min (measured at 230 °C and 2.16 kg) was supplied by Polypropylene Malaysia Sdn. Bhd. and used as the base polymer matrix in this study. To improve interfacial adhesion between the non-polar PP matrix and the hydrophilic bamboo filler, polypropylene-grafted maleic anhydride (PP-g-MA) was employed as a coupling agent. The maleic anhydride groups introduce polar functionality capable of forming covalent bonds with the hydroxyl groups present on the cellulose surfaces of bamboo fibres, thereby enhancing fibre-matrix compatibility. In this work, PP-g-MA (Sigma-Aldrich Co.) containing 8–10 wt.% maleic anhydride and having average molecular weights Mw = 9100 and Mn = 3900 was utilized.

2.1.2 Bamboo filler

The bamboo used in this research was obtained from the *Bambusa blumeana* species, commonly known as Spiny Bamboo or Thorny Bamboo which grows abundantly in Malaysia. This tropical clumping bamboo species is characterized by slightly arching green culms reaching 15-25 m in height, 25-35 cm internode length, 8-15 cm diameter, and an average wall thickness of 2-3 cm. Bamboo chips (Figure 1) were first produced using a mechanical cleaver, then ground with a hammer mill equipped with a 28-mesh screen to obtain fine bamboo filler powder (Figure 2). Prior to compounding, the filler was oven-dried at 80 °C for 24 hours in a convection oven to remove residual moisture. No additional chemical treatment was performed before mixing to ensure that the natural characteristics of the bamboo filler were preserved for analysis.



Fig. 1. Bamboo chips



Fig. 2. Bamboo filler

2.1.3 Melt Compounding and composite formulation

The bamboo-based PP composites were prepared through melt compounding using a 20 mm twin-screw extruder with a 40 L/D ratio (Lab Tech Engineering Company Ltd). The composite formulations consisted of PP (67, 72, 77, 82, 87, 92, and 100 wt%), bamboo filler (0, 5, 10, 15, 20, 25, and 30 wt%), and a fixed 3 wt% of polypropylene-grafted maleic anhydride (PP-g-MA) as a coupling agent, as detailed in Table 1. The compounding process was carried out at a barrel temperature of 180 °C and a screw speed of 120 rpm to ensure uniform dispersion of the bamboo filler within the polymer matrix. The extruded strands were air-cooled and subsequently pelletized using a pelletizer (Lab Tech Engineering Company Ltd). To eliminate residual moisture, the resulting pellets were dried at 80 °C for 24 hours in a vacuum oven and then cooled to room temperature.

Table 1

Blend design

Sample code	PP (%)	Bamboo filler (%)	PP-g-MA (%)
PPBF_0	100	0	0
PPBF_5	92	5	3
PPBF_10	87	10	3
PPBF_15	82	15	3
PPBF_20	77	20	3
PPBF_25	72	25	3
PPBF_30	67	30	3

2.2 Optimization Experiment of Unfilled Polypropylene (PP) Gears

The first phase of the optimization experiment in this research focuses on developing a hybrid optimization approach that integrates the robust parameter design of the Taguchi method with the statistical capabilities of Grey Relational Analysis (GRA) and Principal Component Analysis (PCA) to determine the optimal process parameters for injection-moulded unfilled PP gears. During this phase, the influence of each processing parameter on multiple quality characteristics was systematically analyzed. The selected performance indicators included shrinkage behavior at the gear tooth thickness, addendum, and dedendum circles, as well as tensile ultimate strength, Young's modulus, elongation at break, and maximum load. These parameters collectively represent the dimensional stability and mechanical performance of the PP gears. The overall methodological framework for this first phase of optimization is illustrated in Figure 3, and the detailed descriptions of each experimental stage are provided in the subsequent sections.

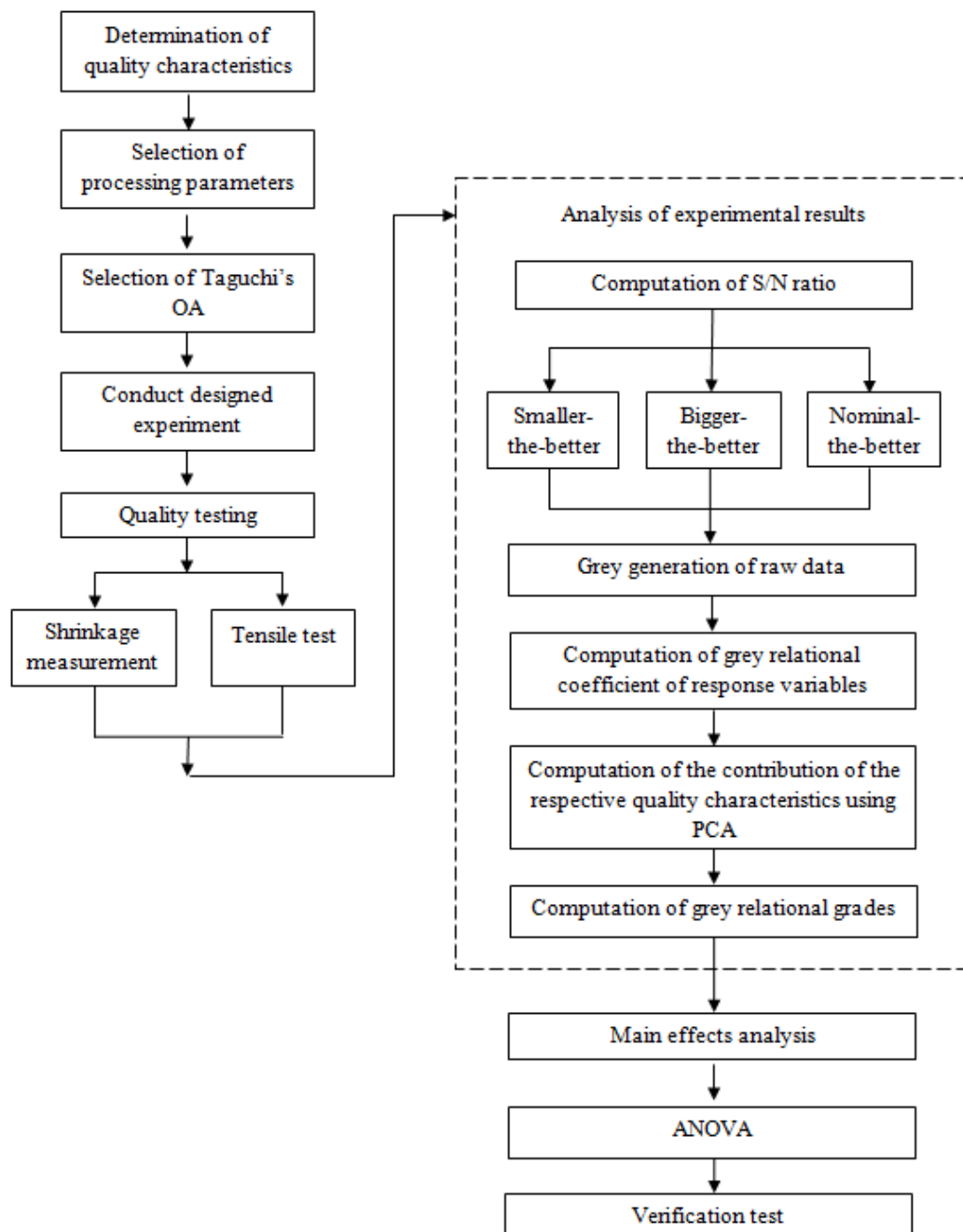


Fig. 3. Experimental flowchart of the first-phase optimization process

2.2.1 Determination of quality characteristics

In the fast-growing plastic gear industry, optimizing multiple quality characteristics is crucial to ensure reliable performance. The dimensional stability of the involute profile greatly affects gear accuracy, as mould cavity shrinkage during cooling can cause warpage and deformation, leading to issues such as tooth fatigue, wear, and creep. Therefore, in this research, the shrinkage behaviour of the tooth thickness, addendum, and dedendum circles (Figure 4) was selected as key quality characteristics. Additionally, tensile strength, Young's modulus, elongation at break, and maximum load were also analyzed to better understand the gear's mechanical performance.

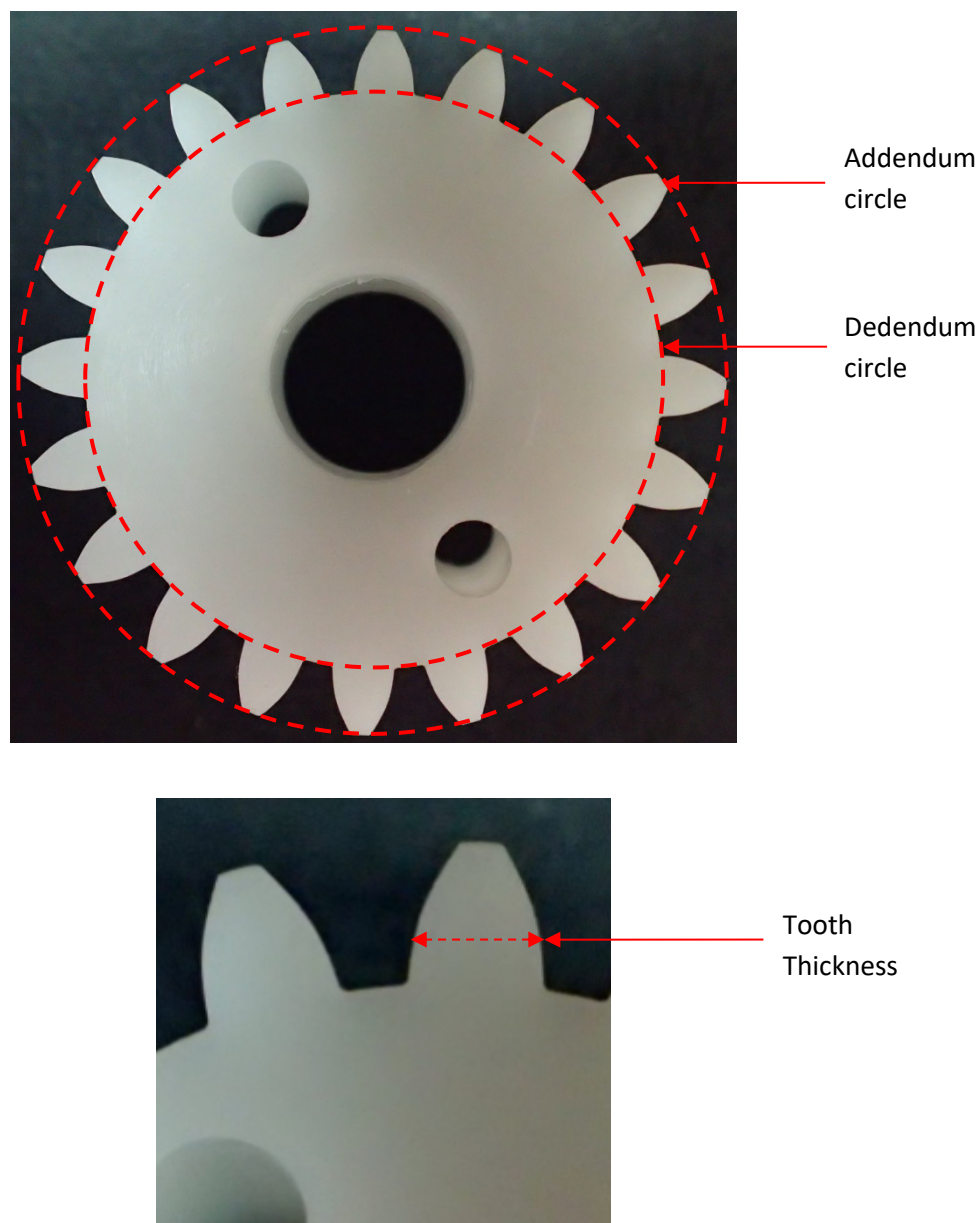


Fig. 4. Gear tooth thickness, addendum and dedendum circles

2.2.2 Selection of processing parameters

Four key process parameters namely melting temperature, packing pressure, packing time, and cooling time were selected for optimization to minimize shrinkage in the tooth thickness, addendum, and dedendum circles, while simultaneously enhancing tensile strength, Young's modulus, elongation at break, and maximum load of the moulded gears. Other processing conditions, including mould temperature (30 °C), injection pressure (80 bar), and stroke distance (60 mm), were kept constant throughout the experiments. Each selected parameter was evaluated at three levels, consistent with the simulation setup. The injection moulding parameters and their corresponding levels are summarized in Table 2.

Table 2

Processing parameters and their levels in the optimization experiment

Column	Factors	Level 1	Level 2	Level 3
A	Melting temperature (°C)	200	220	240
B	Packing pressure (%)	60	80	100
C	Packing time (s)	5	10	15
D	Cooling time (s)	30	40	50

2.2.3 Selection of Taguchi's orthogonal array (OA)

After identifying the process parameters and their respective levels, a suitable OA was selected to design the experimental layout. Since the optimization experiment involved four process parameters, each with three levels, the total degree of freedom (DOF) was calculated as 8. Accordingly, an L9 OA was employed to organize the experimental runs, covering the factors of melting temperature, packing pressure, packing time, and cooling time. The detailed experimental layout based on the L9 orthogonal array is presented in Table 3.

Table 3

Design of experiment using L9 OA

Trial No	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.2.4 Quality testing

2.2.4.1 Shrinkage measurement

The Rax Vision DC 3000 Mitutoyo profile projector was employed to assess the dimensional accuracy of the moulded gear's involute tooth profile. Measurements were performed in two dimensions (2D) to evaluate tooth thickness, addendum, and dedendum circles by profiling selected coordinate points along the gear teeth. Using high magnification and micrometer precision, the profile projector ensured accurate readings. For the addendum and dedendum measurements, twenty edge points per gear tooth were analyzed. To verify repeatability, five gears from the same production batch were measured for comparison of geometric consistency. The relative shrinkage (S) for each quality characteristic was calculated using Equation (1).

$$S = (D_m - D) / D_m \times 100\% \quad (1)$$

Where S is shrinkage, D is the reading of diameter measurement using profile projector and D_m is the mould dimension.

2.2.4.2 Tensile test

A custom split-disc test fixture made from Grade 304 stainless steel was designed and fabricated to apply various stress conditions using a single setup compatible with standard plastic gear testing systems. During the tensile test, the gear specimen was mounted on the fixture with the test section aligned along the split area to ensure accurate positioning along the centerline between the fixture's attachment points. The complete testing assembly of the fixture and gear specimen is shown in Figure 5. Tensile testing was conducted in a controlled environment (20 °C and 50% RH) at a crosshead speed of 3 mm/min, using an Instron 3367 universal testing machine equipped with a 50 kN load cell. The tensile properties including elongation at break, ultimate tensile stress, and Young's modulus were determined from the recorded stress-strain curves of the tested specimens.

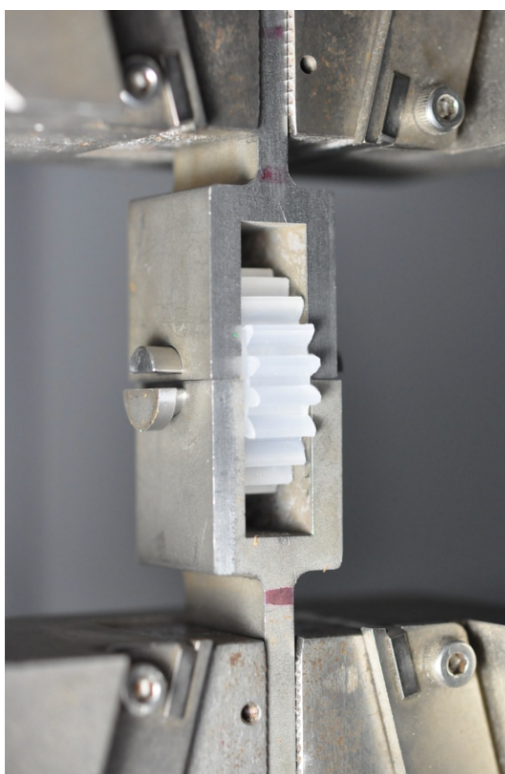


Fig. 5. Setup of test fixture

2.3 Optimization Experiment of Bamboo-Based PP Gear

After determining the optimal combination of processing parameters for the unfilled PP gears in the first phase, a subsequent experiment was carried out using bamboo-filled PP composites. In this second phase, the composite formulations listed in Table 1 were moulded into gears using the same optimized processing conditions identified in the first phase of the optimization experiment. The objective of this phase was to evaluate the feasibility and reliability of bamboo filler as a reinforcement material in plastic gear manufacturing. In this stage of the experiment, the influence of bamboo filler loading on key quality characteristics was systematically examined. The analysis focused on shrinkage behavior at the tooth thickness, addendum, and dedendum circles, as well as on tensile ultimate strength, Young's modulus, elongation at break, and maximum load, to comprehensively evaluate the performance of bamboo-based PP composite gears.

3. Results and discussion

3.1 Analysis of the Optimization Results for Unfilled PP Gear

In this study, the results of shrinkage behavior and tensile properties were analyzed using a hybrid optimization approach that integrates the Taguchi method, GRA, and PCA. The analysis process began with the calculation of signal-to-noise (S/N) ratios, followed by the grey generation of raw data and the determination of grey relational coefficients for each response variable. Subsequently, PCA was applied to evaluate the contribution of each quality characteristic, and finally, the grey relational grade was computed to identify the overall optimal parameter settings.

3.1.1 Signal-to-noise (S/N) analysis

In the processing optimization, all the raw data of shrinkage and tensile properties obtained were converted into S/N ratios using the mean square deviation (MSD) method and listed in Table 4. Since the goal was to achieve minimal shrinkage in tooth thickness, addendum, and dedendum circles, and maximum mechanical performance in terms of tensile strength, Young's modulus, elongation at break, and maximum load, two S/N ratio criteria were applied. The "smaller-the-better" formula was used for shrinkage characteristics, while the "larger-the-better" formula was applied to the mechanical properties.

Table 4
S/N ratios results

Trial No	Shrinkage behaviour			Tensile properties			
	Tooth thickness	Addendum circle	Dedendum circle	Ultimate strength	Young's modulus	Elongation at break	Maximum load
1	29.157	33.516	34.080	13.064	30.514	27.615	67.060
2	25.013	33.428	34.046	13.452	30.319	28.771	67.426
3	22.223	33.871	34.489	13.692	30.139	29.379	67.682
4	19.254	33.965	34.154	13.807	30.090	29.251	67.787
5	19.170	33.352	33.751	13.988	29.993	29.356	67.942
6	18.487	33.527	34.304	13.878	30.238	29.180	67.855
7	20.413	33.872	34.603	13.061	29.787	27.796	67.055
8	17.688	34.659	35.196	11.395	29.679	23.717	65.411
9	19.918	34.095	35.433	12.342	29.489	25.854	66.373

3.1.2 Grey generation of raw data

In the GRA, the S/N ratio results for the seven quality characteristics which are shrinkage behavior at the tooth thickness, addendum, and dedendum circles, along with tensile ultimate strength, Young's modulus, elongation at break, and maximum load (as shown in Table 4) were normalized to values between 0 and 1. The resulting grey relational generation values for these seven characteristics are presented in Table 4.

Table 4
The sequences after data pre-processing (grey generation)

Trials	Shrinkage behaviour			Tensile properties			
	Tooth thickness	Addendum circle	Dedendum circle	Ultimate strength	Young's modulus	Elongation at break	Maximum load
Reference sequence	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Comparability sequence							
1	0.0000	0.8743	0.9757	0.6436	1.0000	0.6884	0.6516
2	0.3613	0.9412	1.0000	0.7932	0.8101	0.8926	0.7962
3	0.6045	0.6026	0.6806	0.8859	0.6349	1.0000	0.8973
4	0.8635	0.5308	0.9221	0.9302	0.5869	0.9773	0.9389
5	0.8707	1.0000	1.2133	1.0000	0.4921	0.9959	1.0000
6	0.9303	0.8659	0.8143	0.9575	0.7309	0.9649	0.9658
7	0.7623	0.6020	0.5987	0.6427	0.2909	0.7204	0.6496
8	1.0000	0.0000	0.1706	0.0000	0.1854	0.0000	0.0000
9	0.8055	0.4317	0.0000	0.3652	0.0000	0.3774	0.3803

3.1.3 Determination of deviation sequence

The deviation sequence $\Delta 0i(k)$ is the absolute difference between the reference sequence $x_0^{**}(k)$ and the comparability sequence $x_i^{**}(kk)$ after normalization. It is determined using Equation (2) and listed in Table 5.

$$xi^*(k) = \frac{xi^0(k)}{xi^0(1)}$$

(2)

Table 5
The deviation sequences

Deviation sequences	Shrinkage behaviour			Tensile properties			
	Δ_{01}	Δ_{02}	Δ_{03}	Δ_{04}	Δ_{05}	Δ_{06}	Δ_{07}
Trial 1	1.0000	0.1257	0.0243	0.3564	0.0000	0.3116	0.3484
Trial 2	0.6387	0.0588	0.0000	0.2068	0.1899	0.1074	0.2038
Trial 3	0.3955	0.3974	0.3194	0.1141	0.3651	0.0000	0.1027
Trial 4	0.1365	0.4692	0.0779	0.0698	0.4131	0.0227	0.0611
Trial 5	0.1293	0.0000	0.2133	0.0000	0.5079	0.0041	0.0000
Trial 6	0.0697	0.1341	0.1857	0.0425	0.2691	0.0351	0.0342
Trial 7	0.2377	0.3980	0.4013	0.3573	0.7091	0.2796	0.3504
Trial 8	0.0000	1.0000	0.8294	1.0000	0.8146	1.0000	1.0000
Trial 9	0.1945	0.5683	1.0000	0.6348	1.0000	0.6226	0.6197

3.1.4 Determination of Grey Relational Coefficient (GRC)

Grey relational coefficients for each of the quality characteristics have been calculated by substituting the distinguishing coefficient, $\psi = 0.5$, using Equation (3). Table 6 lists the grey relational coefficients for each trial of the L_9 OA.

$$\gamma(x_0(k), x_i(k)) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{0i}(k) + \zeta \Delta_{max}}$$

(3)

Table 6

The calculated grey relational coefficient for nine comparability sequences

Trials	Grey relational coefficient						
	Tooth thickness	Addendum circle	Dedendum circle	Ultimate strength	Young's modulus	Elongation at break	Maximum load
1	0.3333	0.7991	0.9536	0.5838	1.0000	0.6161	0.5893
2	0.4391	0.8948	1.0000	0.7074	0.7248	0.8232	0.7105
3	0.5584	0.5572	0.6102	0.8142	0.5779	1.0000	0.8296
4	0.7855	0.5159	0.8652	0.8775	0.5476	0.9566	0.8911
5	0.7946	1.0000	0.7009	1.0000	0.4961	0.9918	1.0000
6	0.8777	0.7885	0.7291	0.9217	0.6501	0.9344	0.9360
7	0.6778	0.5568	0.5547	0.5832	0.4135	0.6414	0.5879
8	1.0000	0.3333	0.3761	0.3333	0.3803	0.3333	0.3333
9	0.7200	0.4680	0.3333	0.4406	0.3333	0.4454	0.4465

3.1.5 Computation of the contribution of the respective quality characteristics using PCA

To optimize problems involving multiple quality characteristics, it is essential to assign appropriate weighting values to each parameter. Traditionally, these weights are determined through experience or trial-and-error, which can introduce uncertainty and subjectivity into the decision-making process. To overcome this limitation, PCA was applied in this study to objectively determine the relative importance of each quality characteristic. PCA was integrated with GRA to calculate the corresponding weights. The grey relational coefficients obtained from GRA (Table 6) were used as input data for PCA, which generated the correlation coefficient matrix using Equation (4) and the corresponding eigenvalues and eigenvectors using Equation (5). The correlation coefficient matrix is shown in Table 7, while Tables 8 and Table 9 present the resulting eigenvalues and eigenvectors computed using statistical software.

$$R_{jl} = \left(\frac{Cov(x_i(j), x_i(l))}{\sigma_{xi(j)} \sigma_{xi(l)}} \right), j = 1, 2, 3, \dots, n; l = 1, 2, 3, \dots, n$$

(4)

Where $Cov(x_i(j), x_i(l))$: the covariance of sequences $x_i(j)$ and $x_i(l)$; $\sigma_{xi(j)}$: the standard deviation of sequence $x_i(j)$; $\sigma_{xi(l)}$: the standard deviation of sequence $x_i(l)$.

$$(R - \lambda_k I_m) V_{ik} = 0$$

(5)

Where λ_k eigenvalues, $\sum_{k=1}^n \lambda_k = n$, $k = 1, 2, \dots, n$; $V_{ik} = [a_{k1} a_{k2} \dots a_{kn}]^T$: eigenvectors corresponding to the eigenvalue λ_k .

The eigenvectors corresponding to each eigenvalue (Table 9) indicate the contribution of each quality characteristic to the respective principal component, with the square of each eigenvector value representing its contribution magnitude. The principal component with the highest variance percentage reflects the most significant influence on the overall quality characteristics. As shown in Table 8, the first principal component accounts for 61.57% of the total variance, making it the primary contributor. Therefore, the squared eigenvectors from this component were used to determine the contribution of each quality characteristic namely shrinkage behavior at the tooth thickness,

addendum, and dedendum circles, along with tensile ultimate strength, Young's modulus, elongation at break, and maximum load as presented in Table 10.

Table 7

Correlation coefficient matrix for each quality characteristic

Variables	Tooth thickness	Addendum circle	Dedendum circle	Ultimate strength	Young's modulus	Elongation at break	Maximum Load
Tooth thickness	1	-0.412	-0.605	-0.015	-0.723	-0.144	-0.016
Addendum circle	-0.412	1	0.682	0.647	0.570	0.576	0.635
Dedendum circle	-0.605	0.682	1	0.532	0.834	0.566	0.530
Ultimate strength	-0.015	0.647	0.532	1	0.249	0.968	1.000
Young's modulus	-0.723	0.570	0.834	0.249	1	0.283	0.250
Elongation at break	-0.144	0.576	0.566	0.968	0.283	1	0.971
Maximum Load	-0.016	0.635	0.530	1.000	0.250	0.971	1

Table 8

The eigenvalues and explained percentage of variation for principal components

Component	Eigenvalues	Variability (%)	Accumulative (%)
First component	4.3096	61.5656	61.5656
Second component	1.8856	26.9378	88.5034
Third component	0.3730	5.3287	93.8322
Fourth component	0.3071	4.3866	98.2187
Fifth component	0.1137	1.6244	99.8431
Sixth component	0.0109	0.1561	99.9992
Seven component	0.0001	0.0008	100.0000

Table 9

The eigenvectors for principal components

Quality Characteristics	First component	Second component	Third component	Fourth component	Fifth component	Sixth component	Seven component
Tooth thickness	-0.216	0.570	0.307	0.702	-0.032	0.200	-0.005
Addendum circle	0.401	-0.082	0.863	-0.237	0.035	0.174	-0.022
Dedendum circle	0.408	-0.286	-0.112	0.453	0.729	-0.050	-0.009
Ultimate strength	0.418	0.359	-0.059	-0.019	-0.110	-0.414	0.714
Young's modulus	0.318	-0.487	-0.056	0.464	-0.660	0.084	0.013
Elongation at break	0.421	0.303	-0.365	-0.172	-0.015	0.754	0.001
Maximum Load	0.417	0.360	-0.090	-0.014	-0.135	-0.425	-0.700

Table 10

The contribution of each individual quality characteristic for the principal component

Quality characteristic	Contribution
Tooth thickness	0.0467
Addendum circle	0.1606
Dedendum circle	0.1665
Ultimate strength	0.1745
Young's modulus	0.1010
Elongation at break	0.1768
Maximum Load	0.1738

3.1.6 Computation of grey relational grades

After obtaining the contribution of each individual quality characteristic for the principal component, the grey relational grades are calculated by adopting modified Equation (6). Calculated grey relational coefficient for nine comparability sequences after PCA are listed in Table 11.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \varepsilon_i(k) \quad (6)$$

Table 11

Calculated grey relational coefficient for nine comparability sequences after PCA

Trials	Grey relational grade							Total Grey relational grade
	Tooth thickness	Addendum circle	Dedendum circle	Ultimate strength	Young's modulus	Elongation at break	Maximum load	
1	0.0156	0.1283	0.1588	0.1019	0.1010	0.1089	0.1024	0.7169
2	0.0205	0.1437	0.1665	0.1234	0.0732	0.1455	0.1235	0.7964
3	0.0261	0.0895	0.1016	0.1421	0.0584	0.1768	0.1442	0.7386
4	0.0367	0.0828	0.1441	0.1531	0.0553	0.1691	0.1549	0.7960
5	0.0371	0.1606	0.1167	0.1745	0.0501	0.1754	0.1738	0.8882
6	0.0410	0.1266	0.1214	0.1608	0.0657	0.1652	0.1627	0.8434
7	0.0317	0.0894	0.0924	0.1018	0.0418	0.1134	0.1022	0.5725
8	0.0467	0.0535	0.0626	0.0582	0.0384	0.0589	0.0579	0.3763
9	0.0336	0.0752	0.0555	0.0769	0.0337	0.0787	0.0776	0.4312

Referring to Table 11, the grey relational grades for each quality characteristic and the corresponding total grey relational grades for the nine experimental trials were presented. The results show that Trial 5 achieved the highest total grey relational grade (0.8882), indicating the most favorable combination of processing parameters in optimizing multiple performance characteristics simultaneously. In contrast, Trial 8 recorded the lowest total grey relational grade (0.3763), suggesting that its parameter setting produced the least desirable results. Overall, the variation in grey relational grades across trials demonstrates that the processing parameters significantly affect both the dimensional stability and mechanical properties of the injection-moulded unfilled PP gears. The total grey relational grade values obtained were subsequently used to determine the optimal processing parameter levels in the main effects analysis.

4. Main Effect Analysis for First Phase

A main effect represents the influence of an independent variable on a dependent variable, averaged over the levels of other factors. To determine the mean response for each level of the

processing parameters, the average performance was calculated based on the total grey relational grade (Table 11). The main effects of the remaining processing parameters including packing pressure (B), packing time (C), and cooling time (D) are summarized in Table 12.

Table 11

Main effects analysis for multiple quality characteristics

Column	Processing parameter	Level 1	Level 2	Level 3
A	Melting temperature (°C)	0.7506	0.8425	0.4600
B	Packing pressure (%)	0.6952	0.6870	0.6711
C	Packing time (s)	0.6455	0.6745	0.7331
D	Cooling time (s)	0.6788	0.7374	0.6370

For better interpretation of the main effect analysis, the results in the Table 11 can be presented graphically, as shown in Figure 6, to demonstrate the impact of variation in processing parameters on multiple quality characteristics of the gear produced.

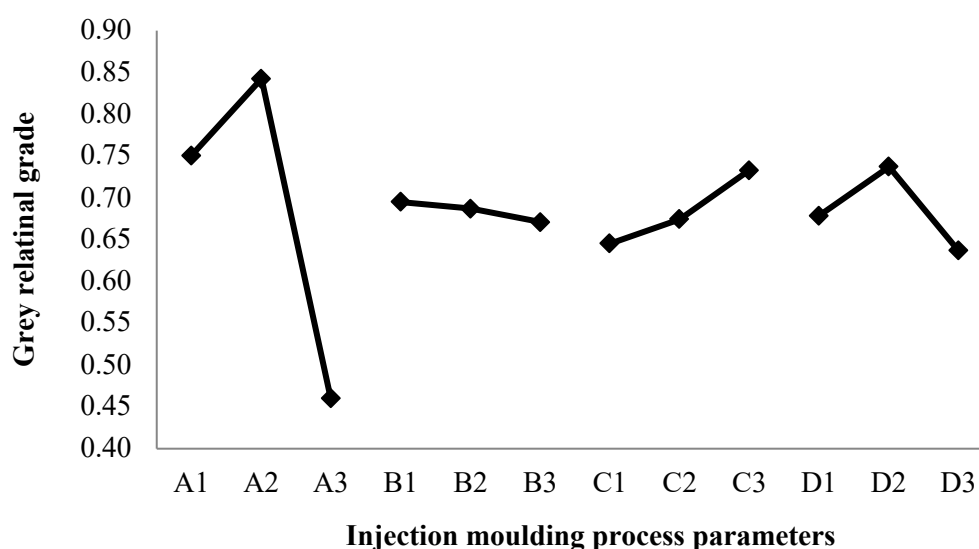


Fig. 6. Main effects plot for multiple quality characteristics

As shown in Figure 6, the multiple quality characteristics, represented by the total grey relational grades, are significantly affected by variations in processing parameters. Since the grey relational grade reflects the correlation between the reference and comparability sequences, a higher-grade value indicates a stronger correlation and, consequently, better overall quality performance. Figure 6 shows that the grey relational grade increases with melting temperature and cooling time from Level 1 to Level 2, but drops at Level 3, when the melting temperature and cooling time reach 240 °C and 50 s, respectively. Similarly, as packing time increases from Level 1 to Level 3, the grey relational grade consistently improves, suggesting that a longer packing time contributes to enhanced part quality. In contrast, packing pressure exhibits an opposite trend, where lower pressure levels produce higher grey relational grades, implying that excessive pressure may negatively affect the gear's dimensional stability or mechanical integrity. Overall, the graph clearly demonstrates that the multiple quality characteristics of the unfilled PP gear are highly sensitive to changes in processing parameters. Based on the main effects analysis, the optimal combination of parameters corresponding to the highest grey relational grades are A2 (melting temperature = 220 °C), B1

(packing pressure = 60%), C3 (packing time = 15 s), and D2 (cooling time = 40 s). These optimized settings are predicted to minimize shrinkage in the tooth thickness, addendum, and dedendum circles, while simultaneously enhancing tensile strength, Young's modulus, elongation at break, and maximum load of the injection-moulded unfilled PP gear.

5. Analysis of Variance (ANOVA) for First Phase

To evaluate the influence of injection moulding parameters on the multiple quality characteristics of unfilled PP gears, an Analysis of Variance (ANOVA) based on the Taguchi method was conducted using the grey relational grades of the nine comparability sequences. ANOVA provides a quantitative assessment of the relative contribution of each processing parameter to the overall quality performance. The degrees of freedom (DOF), sum of squares, variance, and percentage contribution for each parameter were calculated and are summarized in Table 12.

Table 12

ANOVA table for the grey relational grade of nine comparability sequences

Column	Parameters	DOF	Sum of squares	Variances	Percent
A	Melting temperature	2	0.2392	0.1196	89.48
B	Packing pressure	2	0.0009	0.0005	0.34
C	Packing time	2	0.0119	0.0060	4.47
D	Cooling time	2	0.0153	0.0076	5.72
All others/error		0	0.0000		
Total		8	0.2673		100.00

To analyze the results of the second-phase experiment, the percentage contribution of each processing parameter was calculated directly from the sum of squares, as the degrees of freedom (DOF) for the error term were zero. This statistical approach is critical in the context of the Taguchi method, which is designed for robust experimental design and analysis, particularly when assessing the influence of various parameters on outcomes [28]. This percentage contribution reflects the relative significance of each parameter in influencing the multiple quality characteristics, including shrinkage behavior at the tooth thickness, addendum, and dedendum circles, as well as the tensile ultimate strength, Young's modulus, elongation at break, and maximum load of the unfilled PP moulded gear.

According to Roy [29], a parameter can be considered insignificant if its influence is less than 10% of that of the most dominant parameter. Based on the ANOVA results in Table 4.15, melting temperature is identified as the most influential processing parameter, contributing 89.48% to the overall quality improvement. This indicates that melting temperature plays a critical role in minimizing shrinkage and enhancing the mechanical properties of the gear. The dominant contribution of melt temperature (89.48%) can be attributed to its strong influence on polymer chain mobility and melt viscosity. At optimal temperatures, enhanced flow promotes uniform cavity filling and better molecular orientation, reducing residual stresses and shrinkage. Conversely, excessive temperatures can degrade the polymer matrix, leading to strength deterioration. In contrast, cooling time (5.72%), packing time (4.47%), and packing pressure (0.34%) show relatively minor effects, each falling below the 10% significance threshold, and are therefore considered statistically insignificant in this optimization analysis.

6. Verification Test

Once the optimal levels of the injection moulding process parameters are identified, the subsequent step is to verify the improvements in the quality characteristics by using the optimal combination. A verification test can be used to assess the accuracy of the proposed hybrid Taguchi/GRA/PCA optimization method. An experimental verification test is conducted, using the same procedures as previous runs under the optimal process conditions obtained, namely, A2, B1, C3, and D2, to produce the optimized unfilled PP moulded gear. The experimental performance of the optimized unfilled PP gears is presented in Table 13.

Table 13 presents the average values of shrinkage behavior and tensile properties obtained from five specimens of unfilled PP moulded gears. The findings show that the average shrinkage at the tooth thickness was 0.0502 mm, while the addendum and dedendum circles recorded smaller shrinkage values of 0.0147 mm and 0.0140 mm, respectively. These results indicate that the moulded gears maintained good dimensional stability with minimal deformation. In terms of mechanical performance, the gears achieved an average ultimate tensile strength of 5.086 MPa and an average Young's modulus of 32.807 MPa, reflecting consistent stiffness and strength. The average elongation at break was 36.50%, demonstrating reasonable flexibility before failure, and the maximum load capacity reached 2520.18 N, indicating a strong resistance to applied stress. Overall, these results confirm that the unfilled PP gears possess stable geometry and reliable mechanical performance, serving as a solid reference for comparison with bamboo-filled PP composite gears in subsequent optimization studies.

Table 13

Verification results of optimization process

Criteria	Specimen					Average
	1	2	3	4	5	
Shrinkage behaviour						
Tooth thickness (mm)	0.0554	0.0441	0.0470	0.0497	0.0545	0.0502
Addendum circle (mm)	0.0138	0.0141	0.0154	0.0147	0.0155	0.0147
Dedendum circle (mm)	0.0131	0.0138	0.0143	0.0137	0.0149	0.0140
Tensile properties						
Ultimate strength (MPa)	4.887	4.995	5.341	4.873	5.332	5.086
Young's modulus (MPa)	33.634	32.645	33.683	32.057	32.018	32.807
Elongation at break (%)	42.201	30.927	40.661	27.940	40.781	36.502
Maximum Load (N)	2415.245	2457.474	2646.049	2425.638	2656.493	2520.180

7. Impact of Bamboo Filler

Considering the abundant availability and renewability of natural fillers, particularly bamboo, along with the urgent need to address the growing issue of glass- and carbon-filled plastic waste, this study explores the effects of incorporating bamboo fillers at different compositions, with a focus on gear applications. The impact of bamboo filler loading on the shrinkage behaviour and tensile properties of bamboo-based PP composite gears is presented in Table 14. For comparison, the average shrinkage and tensile properties of the unfilled PP gear, obtained from the verification test (Table 13), are used as a reference for further analysis.

Referring to Table 13, it shows that the average relative shrinkage of the optimized unfilled PP gear was 5.02% for tooth thickness, 1.47% for the addendum circle, and 1.40% for the dedendum circle. When bamboo fillers were incorporated into the PP matrix, the overall shrinkage in these regions decreased noticeably. The shrinkage in tooth thickness, addendum, and dedendum circles

reduced progressively with higher bamboo filler content. Specifically, at filler loadings of 5 wt% to 30 wt%, shrinkage in tooth thickness was reduced by 35.26% to 44.82%, while shrinkage in the addendum and dedendum circles decreased by up to 44.90% and 83.57%, respectively, compared to the unfilled PP gear. These findings suggest that bamboo fillers effectively enhance dimensional stability by restricting excessive polymer contraction during cooling. However, the tensile properties exhibited an opposite trend.

Table 14
Results of bamboo-based PP composite gears

Specimen	Shrinkage				Tensile properties		
	Tooth thickness (mm)	Addendum circle (mm)	Dedendum circle (mm)	Ultimate strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Maximum load (N)
PPBF_5	0.0325	0.0135	0.0086	4.237	33.905	43.981	2163.234
PPBF_10	0.0296	0.0113	0.0075	4.228	33.887	39.627	2159.154
PPBF_15	0.0319	0.0094	0.0029	4.052	35.413	39.102	2085.380
PPBF_20	0.0190	0.0090	0.0035	3.814	34.081	28.077	1971.259
PPBF_25	0.0353	0.0079	0.0021	3.490	34.504	35.673	1799.795
PPBF_30	0.0277	0.0081	0.0023	3.421	33.582	35.140	1772.118

As shown in Table 14, both the ultimate tensile strength and maximum load of the bamboo-based PP composite gears decreased with increasing filler content. The optimized unfilled PP gear recorded an ultimate strength of 5.086 MPa and a maximum load of 2520.180 N. In contrast, at 5 wt% bamboo filler, these values dropped to 4.237 MPa and 2163.234 N, respectively, with further reductions observed at higher filler levels. This decline is likely due to weak interfacial bonding between the hydrophobic PP matrix and the hydrophilic bamboo filler, resulting in poor stress transfer within the composite [30-32]. Similar behavior has been observed in kenaf/PP and jute/PP composites, where untreated fibers cause interfacial voids that hinder stress transfer [33-34]. While the use of PP-g-MA as a coupling agent improves adhesion moderately, further surface modifications such as alkali or silane treatment could enhance fiber-matrix bonding, thereby reducing the strength penalty associated with higher filler loadings.

On the other hand, the tensile Young's modulus of the bamboo-filled composites was generally higher than that of the unfilled PP gear, indicating an increase in stiffness. The unfilled PP gear showed a modulus of 32.807 MPa, while the addition of 5 wt% to 25 wt% bamboo filler increased the modulus by 3.35% to 5.17%, with the 15 wt% composition achieving the highest improvement of 7.94% over the unfilled sample. This trend reflects the typical stiffening effect of natural fillers, which restrict polymer chain mobility and enhance rigidity [35]. The elongation at break also improved moderately as the bamboo filler content increased from 5 wt% to 15 wt%, reaching a peak value of 43.981% at 5 wt%, before decreasing when the filler content rose beyond 20 wt%. This reduction at higher loadings is attributed to filler agglomeration and poor interfacial adhesion, which limit the composite's ability to deform plastically. Overall, these findings demonstrate that bamboo filler incorporation can significantly improve dimensional stability and stiffness of PP gears, though it may reduce tensile strength and ductility at higher filler loadings.

4. Conclusions

This study successfully investigated the multi objective optimization of bamboo filled polypropylene (PP) plastic gears produced through injection moulding by applying a hybrid optimization approach that combines the Taguchi method, Grey Relational Analysis (GRA), and

Principal Component Analysis (PCA). The research was carried out in two main phases: optimization of injection moulding parameters for unfilled PP gears and evaluation of the effects of bamboo filler addition at different compositions on the dimensional and mechanical performance of PP composite gears.

In the first phase, the optimization experiment showed that the processing parameters including melting temperature, packing pressure, packing time, and cooling time are significantly influenced the multiple quality characteristics, including shrinkage behavior (tooth thickness, addendum, and dedendum circles) and tensile properties (ultimate strength, Young's modulus, elongation at break, and maximum load). The optimal parameter combination identified through the hybrid Taguchi/GRA/PCA approach was melting temperature 220 °C, packing pressure 60 percent, packing time 15 seconds, and cooling time 40 seconds. Among these, melting temperature was found to be the most dominant parameter, contributing 89.48 percent to the overall quality improvements, while the other parameters had comparatively smaller effects. The optimization process successfully minimized shrinkage and improved mechanical consistency in unfilled PP gears, demonstrating the reliability of the hybrid method in solving multi objective optimization problems.

In the second phase, the feasibility of using bamboo filler as a natural reinforcement in PP gears was examined. The results showed that incorporating bamboo filler effectively reduced shrinkage in the gear's tooth thickness, addendum, and dedendum circles, indicating improved dimensional stability. The shrinkage reduction ranged from 35 to 83 percent depending on the filler loading level. However, the tensile strength and maximum load decreased as the bamboo filler content increased, likely due to weak interfacial bonding between the hydrophobic PP matrix and hydrophilic bamboo fibers. Despite this, the tensile Young's modulus increased with higher bamboo filler content, indicating greater stiffness and rigidity. Moderate filler additions (5 to 15 wt%) also improved elongation at break, while excessive loading (above 20 wt%) reduced ductility due to filler agglomeration. Overall, this research confirms that bamboo filler is a promising sustainable and cost-effective alternative to conventional synthetic fillers in plastic gear manufacturing. The integration of Taguchi, GRA, and PCA provided a practical and systematic framework for optimizing multiple performance characteristics in injection moulding. In conclusion, the bamboo-based PP composite gears achieved a balanced combination of dimensional accuracy, mechanical performance, and environmental sustainability. Future work is recommended to explore surface treatment of bamboo filler to improve interfacial bonding and to test the gears under real operating conditions, such as wear, friction, and fatigue, to validate their potential for power transmission applications.

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