Experimentally Predicted Optimum Processing Parameters Assisted by Numerical Analysis on the Multi-physicomechanical Characteristics of Coir Fiber Reinforced Recycled High Density Polyethylene Composites

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Research Article

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Experimentally predicted optimum processing parameters assisted by numerical analysis on the multi-physicomechanical characteristics of coir fiber reinforced recycled high density polyethylene composites

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ABSTRACT

This paper presents the analysis of processing parameters in the fabrication of coir fiber recycled high density polyethylene composite through experimental data and Taguchi grey relational analysis. Three processing parameters; fiber conditions, fiber length, and fiber loading with mixed level design, having orthogonal array L32 (2**1 4**2) were employed in the preparation of polymer composite. Numerical analysis assisted by Taguchi design was conducted on the experimental multi-physicomechanical characteristics of the polymer composite for optimum processing parameters. The optimum grey relational grade was gotten to be 0.8286 and was experimentally validated with 95% confidence interval. The optimum processing parameters were discovered to be a treated fiber having 8 mm length at 30% loading. Although, other processing parameters are significant, but fiber loading is the most significant parameter. Correspondingly, the contribution of residual error on the overall multi-physicomechanical characteristics is insignificant having 2.43% of contribution.

Keywords: Coir fiber; optimization; Taguchi grey relational analysis; Recycled high density polyethylene; numerical analysis

1.0 Introduction

Environmentally friendly materials have received enormous attention in this recent time, and natural fibers are environmentally friendly materials, which exhibit better properties and are cheaper compared with its synthetic counterparts [1, 2].

Polymers are generally classified as thermoplastics and thermosets. Thermoplastics are usually softer at a relative higher temperature and they do regain their original properties when they are cooled, while thermosets is highly cross-linked and can be only treated when heated, sometimes with the help of pressure/light irradiation [3]. Significantly, for the mechanical properties of natural fiber polymer composite (NFPC) to be enhanced, high fiber loading is essential. There have been reports showing that increase in fiber have led to increase in composites tensile strength [4]. One way to improve the compatibility with the hydrophobic polymer matrix is the fiber treatment.

Polymer matrix impregnated with natural fiber of high strength is a natural fiber polymer composites (NEPC) [5].

Moreover, recycled HDPE is a potential material with a suitable matrix. It is abundant globally, due to the fact that it is relatively cheap, easy to be processed and have some desirable properties [6]. Because HDPE is a disposable container, it is easier to be recycled, coupled with the fact that it is very much compatible with fiber reinforcement. Its low melting point makes it less susceptible to degradation, even though some reports have shown that it degrades, especially when it is cross-linked, but it can be mitigated through some treatment processes such as alkali treatment [7]. Surface treatment is essential when it comes to improving natural fiber/plastic bonds, but majority of its techniques employed expensive equipment and chemicals [8]. However, some techniques, for instance, alkali treatment of natural fibers, salane coupling, etc. are not expensive. Hence, in this work, we employed alkali treatment technique to improve the coconut fiber's properties for better mechanical and water absorption competence, which can make it suitable for some load bearing applications.

Natural fibers have variations in their chemical components depending on the type of natural fiber, its maturity, source and processes. In addition, the combination of natural fiber and processing method makes it essential to find effective parameter setting to obtain high-performance composites. This is to attain a guide for manufacturers and an acceptable standard for high-performance coir fiber composite production. Hence, this study seeks to employ effective optimization technique in finding the best process parameter values for coir fiber recycled high density polyethylene composite production [9].

Taguchi approach is employed in this study for the optimization because it is robust and cost effective. In classical process parameter design, a large number of experiments has to be carried out as the number of the processing parameters increases; making it complex and not easy to use. Taguchi's approach provides an efficient and systematic approach for conducting experiments to determine the optimum setting of design parameters for performance and cost. The Taguchi method uses orthogonal arrays to study a large number of variables using a small number of experiments [10]. The conclusions made from small size experiments are valid over an entire experimental region spanned by the factors and their settings. Taguchi approach can reduce research and production costs by simultaneously studying a large number of parameters. By applying the Taguchi parameter design technique, product and process designs performance can be improved.

Grey relational analysis is augmented with Taguchi design method for multiple performance characteristics of the polymer composite. The Grey relational analysis procedure is used to combine all the considered performance characteristics into a single value that can be used as the single characteristic in optimization problems. Thus, the study will explore simplifying optimization of the complicated multiple performance characteristics of the process using the Taguchi-grey relational analysis. Different studies have been conducted using Taguchi-grey relational analysis to optimize processing factors for multiple performance characteristics. Abifarin [10] employed Taguchi-grey relational analysis to optimize multiple mechanical characteristics of natural hydroxyapatite. Stalin et al. [11] used Taguchi-grey relational analysis and ANN-TLBO algorithm to optimize wear parameters for silicon nitride filled AA6063 matrix composites. Pawade & Joshi [12] optimized multi-objective surface roughness and cutting forces in high-speed turning of Inconel 718 with the help of Taguchi-grey relational analysis. Tzeng et al. [13] optimized multiple performance characteristics of turning operations using Taguchi-grey relational analysis.

In this study, the effect of one surface modification, five levels of fiber loading and five level of fiber lengths on multiple response of coir fiber recycled high density polyethylene composites were investigated. For experiment that has multiple responses, the input factors combination that gives high value in a particular performance characteristic might not be desirable for another. Thus there is a need to find a factor combination that will give desirable values for all the considered performance characteristics, and was done through multi-response optimization using Taguchi gray relational analysis.

2.0 Materials and Method

2.1 Materials

2.1.1 Coir fiber

The coir fiber used was obtained from coconut husk (From Lagos state, Nigeria). The outer layer shell or the mesocarp of the coconut was where the fiber was extracted from. The coconut was gathered from the Arecaceae family of palm, particularly cocus nucifera. Retting process was used for extraction. This process involves allowing the fibers to be separated from the woody core by controlled degradation of the husk [14]. The Coconut Husk were soaked in water for 3 months, to decompose the pulp on the shell, after which the fibers were extracted by pulling them out and the fibers then washed again to remove the embedded dirt between the fibers were then combed were air dried for 48 as posited by Gu [15]. These fibers were cut into varying lengths of 2mm, 4mm, 6mm and 8mm. These cut fibers were treated in 5% NaOH of analytical grade obtained from DOW Chemicals. The fibers were soaked and left for 10 hrs at room temperature. The fibers were then rinsed in distilled water until it was no longer slippery. The fibers were then neutralized with 1% acetic acid. The fibers were dried in open air for 24 hours and placed in an oven at a temperature of 60 degrees Celsius to ensure proper drying.

2.1.2 High density polyethylene (recycled)

The high density polyethylene used in this work was obtained from the empty yoghurt bottles from a particular company simply referred to as SAN yoghurt in the main campus of Ahmadu Bello University, Zaria, Nigeria. They have the monopoly of yogurts sale on campus and therefore have high patronage. This also implies that the bottles are littered everywhere within the school surrounding. The bottles were obtained from their campus depot, washed properly with mild detergent and dried in open air, away from the sun. The dried containers are cut into smaller sizes manually before shredding inti smaller bits using a Worthy Crust Machines, which has a capacity of 81kg, Rev/min of 1440 at a frequency of 50hertz.

2.2 Experimental Design

2.2.1 Taguchi DOE

Taguchi recommends Orthogonal Array (OA) to carry out experiments. Three processing parameters with mixed levels design were considered on the resultant mechanical and physical properties of fiber reinforced HDPE composite. The Table 1a below highlight the experimental design:

Table 1a: Taguchi Design of Experiment (DOE)

Processing parameters	Fiber conditions	Fiber length (mm)	Fiber loading (%)
Level 1	Untreated Fiber (UF)	2	0
Level 2	Treated Fiber (TF)	4	10
Level 3	-	6	20
Level 4	-	8	30

The orthogonal array L32 (2**1 4**2) selected as shown in Table 1b having 32 rows. The considered orthogonal array was based on the design in Table 1a, and was generated in the Minitab, given in Table 1b.

Table 1b: Experimental layout

Experimental no.	Fiber Conditions	Fiber length	Fiber loading
1	UF	2	0
2	UF	2	10
3	UF	2	20
4	UF	2	30
5	UF	4	0
6	UF	4	10
7	UF	4	20
8	UF	4	30
9	UF	6	0
10	UF	6	10
11	UF	6	20
12	UF	6	30
13	UF	8	0
14	UF	8	10
15	UF	8	20
16	UF	8	30
17	TF	2	0
18	TF	2	10
19	TF	2	20

20	TF	2	30
21	TF	4	0
22	TF	4	10
23	TF	4	20
24	TF	4	30
25	TF	6	0
26	TF	6	10
27	TF	6	20
28	TF	6	30
29	TF	8	0
30	TF	8	10
31	TF	8	20
32	TF	8	30

2.3 Composite Formulation

The matrix and the fiber were blended using the two roll mill. The machine was heated for 30-45 minutes to attain a temperature of 180°C. The rear and front rolls co-rotate. The front roller is responsible for the shear force so it rotates faster. It squeezed the material at the nip of the rollers, forming it into a band After the HDPE had melted the filler was added to it. The two-roll mill rotated at 70rpm for 5 minutes. Under this condition, a uniform dispersion and distribution of fibers can be achieved in recycled HDPE. The shredded HDPE is first of all filled in the heated mixing cavity while the rolls are under constant rotational speed. After 4 minutes, the fibers were carefully added into the already melted HDPE and the mixing process was continued for another 2minutes. The rolls are then stopped and the composites removed from the heated roll of the two-roll mill, and cut in a non-uniform sizes which are wide enough to fit into the mold to be used for compression with a little extra. A fiber loading ranging from 10-50% was used. The 8 station compression molding machine was used for this process. It was heated for 40minutes to 1hour to raise the temperature to about 170 °C, a temperature lower than the one used during melting. This is to prevent degradation of the compound. Here, heat and pressure is applied. Before the sample was placed into the machine. The compounded material was then pressed into a 130 by 130 by 3.2 mm mold and the mold was placed in the machine. The sample been molded was held for 1 minute at that temperature under compression before been cooled at room temperature.

2.4 Characterization of Coir Fiber Recycled High Density Polyethylene Composite

2.4.1 Tensile test

Tensile strength was carried out according to ASTM D 638-06 on dumbbell shaped specimens using Universal Testing machine. The testing condition used were crosshead speed 10 mm/min, gauge length of 60 mm and load cell 1 KN. The recorded value is the average of 3 results. Besides the ultimate tensile strength (UTS), percentage of elongation was also obtained from the tensile testing machine [16].

2.4.2 Flexural strength test

Flexural strength is the ability of the composite material to withstand bending forces applied perpendicular to its longitudinal axis. The 3-point flexural test was conducted with a universal testing machine (model 4240). Flexural testing was carried out in accordance with ASTM D790-08 with a span length of 60mm. The dimensions of the specimen in each case was 100 by 30 by 3mm. The flexural strength and flexural modulus of the composite specimens and will be determined using the following equations;

$$\text{Flexural strength} = \frac{3PL}{2bt^2} \tag{1}$$

$$\text{Flexural modulus} = \frac{PL^3}{4bt^3w} \tag{2}$$

L Span length

F Load (N)

b Width(mm)

d thickness(mm)

D deflection (mm)

2.4.3 Impact strength test

The impact strength of a material provides information regarding the energy required to break a specimen of a given dimension, the magnitude of which reflects the material's ability to resist a sudden impact [17]. Three specimens were tested and an average of these results taken. The test was performed in accordance to ASTM E23.

2.4.4 Hardness test

Hardness is the resistance of a material to deformations, indentations or scratching. The method was based on the rate of penetration of a specified indenter forced into the material, under specified conditions. Each sample was subjected to 3 hardness readings at different positions on the sample bases and the average taken. ASTM D2240 (Shore D) was used [18, 26, 27].

2.4.5 Water absorption test

Coir/HDPE composite being bio-based have the tendencies of absorbing water and so it is important to study their water absorption properties with relation to time. This is crucial for optimum utilization [19]. Water absorption is troublesome because it can lead to matrix cracking, dimensional instability, and inferior mechanical properties of the fiber-reinforced polymer composite [20]. Water absorption test was done by taking the difference between the mass of the samples before and after water immersion at intervals according to ASTM standard D 570-98. The measurement was taken every day for the period of 29 days. The formula used to calculate the values is shown in equation 3 [21]:

Moisture Content = $\frac{M_2\text{-}M_1}{M_1} \times 100$ (3)

Where, M_1 = weight of sample before immersion and M_2 = weight of sample after immersion

Figure 1 shows the experimental procedure for the fabrication of coir fiber reinforced recycled high density polyethylene composite.

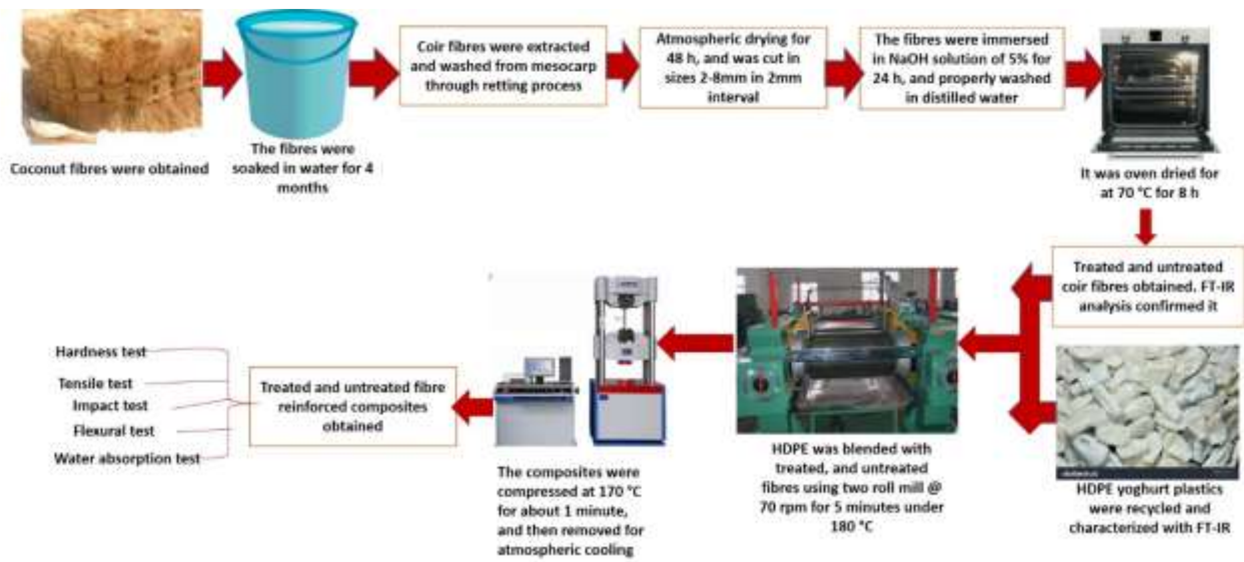

Figure 1: Fabrication of coir fiber reinforced HDPE composite

2.5 Numerical Analysis

The numerical analysis considered in this study was grey relational analysis. The first step of the grey relational analysis is the grey relational generation. During this step, the responses will be normalized in the range between zero and one. Next, the grey relational coefficient will be calculated from the normalized data to express the relationship between the desired and the actual responses. Then, the grey relational grade will be computed by averaging the grey relational coefficient corresponding to each performance characteristic. Overall evaluation of the multiple performance characteristics is based on the grey relational grade. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade. Furthermore, a statistical analysis of variance (ANOVA) is performed to find which process parameters are statistically significant. With the grey relational analysis and statistical analysis of variance, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the analysis. These steps were obtained from Abifarin [10], Lin [24] & Achuthamenon et al. [25]

3.0 Results and Discussion

3.1 Orthogonal Array Experiment

Table 2a and 2b show the experiment results of eight performance characteristics:

Table 2a: Experiment results for Impact strength, hardness, tensile strength and percentage of elongation

Experimental no.	Impact strength (J)	Shore D Hardness	Tensile strength (MPa)	Elongation (%)
1	57.45	45.66	29.478	651.55
2	60.22	74.93	33	602.21
3	62.32	79.16	35.61	587.43
4	64.41	81.93	37.57	546.565
5	57.45	45.66	29.478	651.55
6	61.99	75.1	36	572.29
7	65.76	82.44	38.77	555.24
8	67.79	84.65	42.55	523.65
9	57.45	45.66	29.478	651.55
10	63.31	77.19	38.64	550.921
11	66.87	85.58	39.43	525.78
12	69.15	88.74	45.18	501.098
13	57.45	45.66	29.478	651.55
14	62.34	74.21	40.99	520.21
15	65.55	81.24	42.25	503.812
16	68.99	82.35	48.75	450.128
17	57.45	45.66	29.478	651.55
18	65.67	82.97	37.86	633.11
19	67.55	86.13	39.9	600.22
20	69.98	89.42	43.23	586.986
21	57.45	45.66	29.478	651.55
22	67.45	85.77	43.33	622.98
23	69.54	87.29	48.92	610.82
24	72.12	92.88	53.78	566.686
25	57.45	45.66	29.478	651.55
26	69.36	91.77	45.98	612.138
27	71.88	93.14	52.49	580.232
28	74.3	95.36	55.89	536.686
29	57.45	45.66	29.478	651.55
30	72.21	99.57	47.45	592.8

31	73.56	103.28	55.67	530.38
32	76.99	109.5	59.62	506.188

Table 2b: Experiment results for tensile modulus, flexural strength, flexural modulus and water absorption capacity

Experimental no.	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Water absorption capacity
1	1225.34	44.85968523	1175.12	0.01
2	1325.6	46.11755954	1212.812844	0.03
3	1451.7654	48.34736413	1372.017286	0.05
4	1634.5	52.82860466	1463.676777	0.06
5	1225.34	44.85968523	1175.12	0.01
6	1433.8643	48.87334339	1321.122054	0.04
7	1623.8532	50.23513323	1427.978852	0.06
8	1737.9743	54.29824561	1573.357074	0.08
9	1225.34	44.85968523	1175.12	0.01
10	1554.7455	51.84034858	1532.351437	0.05
11	1789.8754	53.20308444	1659.742615	0.07
12	1896.8532	55.56466093	1787.811095	0.09
13	1225.34	44.85968523	1175.12	0.01
14	1688.464	53.52101624	1782.558745	0.12
15	1894.6533	55.60587526	1961.174772	0.14
16	1919.3515	58.84466273	2116.06412	0.17
17	1225.34	44.85968523	1175.12	0.01
18	1567.8332	48.72541668	133.35155	0.05
19	1744.5747	51.08876534	1456.574081	0.06
20	1845.8716	54.806464	1589.99966	0.09
21	1225.34	44.85968523	1175.12	0.01
22	1719.6423	52.98435298	1443.230246	0.05
23	1829.9413	55.08101415	1553.876977	0.07
24	1941.8632	57.90433621	1678.122485	0.09
25	1225.34	44.85968523	1175.12	0.01
26	1868.8756	54.57004687	1670.586468	0.06
27	1994.7532	57.77324477	1877.812114	0.07
28	1998.8643	59.97641795	1967.450605	0.09
29	1225.34	44.85968523	1175.12	0.01
30	1992.9648	56.69078765	1840.830698	0.19
31	2007.22	59.16532568	2023.58766	0.2
32	2156.332	63.99589525	2347.180521	0.21

3.2 Grey Relational Analysis for the Multiple Performance Characteristics

A linear data preprocessing method employed in this study for the eight performance characteristics is the higher the- better and is expressed as:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{max\, y_i(k) - \min y_i(k)} \tag{4}$$

Where x_i (k) is the value after the grey relational generation, min y_i (k) is the smallest value of y_i (k) for the kth response, and max y_i (k) is the largest value of y_i (k) for the kth response.

Table 3a and 3b show the sequences after the grey relational generation. An ideal sequence is $x_0(k)$ (k= 1, 2… 32) for Impact strength, hardness, tensile strength, percentage of elongation, tensile modulus, flexural strength, flexural modulus and water absorption capacity.

Table 3a: Data processing of Impact strength, hardness, tensile strength and percentage of elongation

Experimental no.	Impact strength	Shore D hardness	Tensile strength	Elongation per
Ideal sequence	1	1	1	1
1	0	0	0	0
2	0.141760491	0.458489975	0.116846925	0.327945125
3	0.249232344	0.524749373	0.203437065	0.426182437
4	0.356192426	0.568139098	0.26846261	0.697797304
5	0	0	0	0
6	0.23234391	0.461152882	0.216375821	0.526812538
7	0.425281474	0.57612782	0.308274169	0.640137718
8	0.529170931	0.610745614	0.433680579	0.850105017
9	0	0	0	0
10	0.299897646	0.493890977	0.30396125	0.668844548
11	0.482088025	0.625313283	0.330170526	0.835947678
12	0.59877175	0.67481203	0.520934245	1
13	0	0	0	0
14	0.250255885	0.447211779	0.381925552	0.872969452
15	0.414534289	0.557330827	0.423727689	0.981961024
16	0.590583419	0.574718045	0.639373631	1.338779146
17	0	0	0	0
18	0.420675537	0.584429825	0.278083737	0.122564007
19	0.516888434	0.633928571	0.345763387	0.341171935
20	0.641248721	0.685463659	0.456240462	0.429133544
21	0	0	0	0
22	0.511770727	0.628289474	0.459558092	0.189894451

23	0.618730809	0.652098997	0.645013602	0.270717571
24	0.750767656	0.739661654	0.806250415	0.564060298
25	0	0	0	0
26	0.609518936	0.722274436	0.547475284	0.261957302
27	0.738485159	0.743734336	0.763452989	0.474024938
28	0.862333675	0.778508772	0.876252405	0.763459442
29	0	0	0	0
30	0.755373593	0.844454887	0.596244443	0.39048999
31	0.824462641	0.902568922	0.86895362	0.805373142
32	1	1	1	0.966168612

Table 3b: Data processing of tensile modulus, flexural strength, flexural modulus and water absorption capacity

Experimental no.	Tensile modulus	Water absorption capacity	Flexural strength	Flexural modulus
Ideal sequence	1	1	1	1
1	0	0	0	0
2	0.107691581	0.1	0.065732677	0.032159469
3	0.243208749	0.2	0.182255467	0.167992423
4	0.439488202	0.25	0.416431437	0.24619614
5	0	0	0	0
6	0.223980765	0.15	0.20974154	0.124568699
7	0.428052228	0.25	0.280904525	0.215738733
8	0.550632336	0.35	0.493230393	0.339775179
9	0	0	0	0
10	0.353822052	0.2	0.364788187	0.304789241
11	0.606380506	0.3	0.436000608	0.413479173
12	0.721287831	0.4	0.559409397	0.522746978
13	0	0	0	0
14	0.49745218	0.55	0.452614755	0.518265682
15	0.718924867	0.65	0.561563132	0.670660565
16	0.745453774	0.8	0.730812292	0.802811888
17	0	0	0	0
18	0.367879853	0.2	0.202011341	-0.888835031
19	0.557721978	0.25	0.325512737	0.240136133
20	0.666527317	0.4	0.519788336	0.353974605
21	0	0	0	0
22	0.530941512	0.2	0.424570369	0.228751196
23	0.649416214	0.3	0.53413549	0.323154795

24	0.769634111	0.4	0.681673694	0.429160846
25	0	0	0	0
26	0.691236445	0.25	0.507433898	0.422731129
27	0.826444481	0.3	0.674823255	0.599535691
28	0.830860308	0.4	0.789954369	0.676015095
29	0	0	0	0
30	0.824523519	0.9	0.618257346	0.567983211
31	0.839835358	0.95	0.74756916	0.723911134
32	1	1	1	1

The definition of grey relational grade in the grey relational analysis is to show the relational degree between the 32 sequences [x_o (k) and x_i (k), i= 1, 2 . . . 32; k= 1, 2 . . . 32]. The grey relational coefficient $\xi_i(k)$ can be calculated as:

$$\xi_i(k) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{oi}(k)+\zeta\Delta_{max}} \tag{5}$$

Where $\Delta_{oi}(k) = \|x_o(k) - x_i(k)\|$= difference of the absolute value between x_o^*(k) and x_i^*(k); ζ = distinguishing coefficient (0~1), but it is generally set at 0.5 to allocate equal weights to every parameter; and x_o^*(k) and x_i^*(k) refer to reference and compatibility sequences, respectively. Δ_{min} and Δ_{max} are the minimum and maximum deviations of each response variable. The grey relational coefficient results for the experimental layout are shown in Table 4a and 4b.

Table 4a: Grey relational coefficient (GRC) for Impact strength, hardness, tensile strength and percentage of elongation

Experimental no.	Impact strength	Shore D hardness	Tensile strength	Elongation per
1	0.333333333	0.333333333	0.333333333	0.333333333
2	0.368123587	0.480072191	0.361492888	0.426601186
3	0.399754501	0.512688725	0.385634963	0.465628443
4	0.437136465	0.536560767	0.405996606	0.623283869
5	0.333333333	0.333333333	0.333333333	0.333333333
6	0.394428744	0.481302774	0.389522111	0.513775629
7	0.465238095	0.541200407	0.419559589	0.581488467
8	0.515023722	0.562268804	0.468902648	0.76935507
9	0.333333333	0.333333333	0.333333333	0.333333333
10	0.41663113	0.496964035	0.418046656	0.601572184
11	0.491201609	0.571633238	0.427412722	0.752952716
12	0.55479841	0.605922551	0.510690929	1
13	0.333333333	0.333333333	0.333333333	0.333333333

14	0.4000819	0.474929326	0.447197413	0.797409315
15	0.460631777	0.530408774	0.464566444	0.965178342
16	0.549803039	0.540375825	0.580972206	3.101335752
17	0.333333333	0.333333333	0.333333333	0.333333333
18	0.463252726	0.546107784	0.409193343	0.362993273
19	0.508589276	0.577319588	0.433186744	0.431470393
20	0.582240763	0.613846154	0.479037539	0.466911628
21	0.333333333	0.333333333	0.333333333	0.333333333
22	0.505955463	0.573584906	0.480565033	0.381648639
23	0.567363531	0.589691483	0.584804625	0.406741354
24	0.667349727	0.657601978	0.720721152	0.534222449
25	0.333333333	0.333333333	0.333333333	0.333333333
26	0.561494253	0.642900302	0.524920762	0.403863292
27	0.656586022	0.661143331	0.678843295	0.48734128
28	0.784109149	0.693009119	0.801606298	0.678849243
29	0.333333333	0.333333333	0.333333333	0.333333333
30	0.671477663	0.762724014	0.553246944	0.450649382
31	0.740151515	0.836916623	0.792334788	0.719810924
32	1	1	1	0.93662533

Table 4b: Grey relational coefficient (GRC) for tensile modulus, flexural strength, flexural modulus and water absorption capacity

Experimental no.	Tensile modulus	Water absorption capacity	Flexural strength	Flexural modulus
1	0.333333333	0.333333333	0.333333333	0.333333333
2	0.359115835	0.357142857	0.348610048	0.340636458
3	0.397838543	0.384615385	0.379436217	0.37537324
4	0.471470474	0.4	0.461438267	0.398786458
5	0.333333333	0.333333333	0.333333333	0.333333333
6	0.391843623	0.37037037	0.387519257	0.363522336
7	0.466440636	0.4	0.410140149	0.38932888
8	0.526666348	0.434782609	0.496637956	0.43095096
9	0.333333333	0.333333333	0.333333333	0.333333333
10	0.436232438	0.384615385	0.440446438	0.418336261
11	0.559522261	0.416666667	0.469925081	0.46018446
12	0.642085766	0.454545455	0.531580901	0.511638223
13	0.333333333	0.333333333	0.333333333	0.333333333
14	0.498729327	0.526315789	0.477379267	0.509302762
15	0.640143283	0.588235294	0.532800891	0.602889455

16	0.662649925	0.714285714	0.650036388	0.71716656
17	0.333333333	0.333333333	0.333333333	0.333333333
18	0.441649238	0.384615385	0.385211378	0.209307044
19	0.530628953	0.4	0.425717686	0.396868275
20	0.599899685	0.454545455	0.51009391	0.436290507
21	0.333333333	0.333333333	0.333333333	0.333333333
22	0.515964729	0.384615385	0.464930467	0.393314038
23	0.587831567	0.416666667	0.517670952	0.424864713
24	0.684588379	0.454545455	0.61100321	0.466923532
25	0.333333333	0.333333333	0.333333333	0.333333333
26	0.61822766	0.4	0.503744787	0.464136683
27	0.742329304	0.416666667	0.605930794	0.555269093
28	0.747228129	0.454545455	0.704180096	0.606807233
29	0.333333333	0.333333333	0.333333333	0.333333333
30	0.740218222	0.833333333	0.567058878	0.536471023
31	0.757386822	0.909090909	0.664512901	0.644256118
32	1	1	1	1

As shown in equation (6), a composite grey relational grade (GRG), is then computed by averaging the GRC of each response variable, according to Abifarin [10]:

$$\gamma_i = \frac{1}{n}\sum_{i=1}^{n} \xi_i(k) \qquad (6)$$

Where γ_i= the value of GRG determined for the ith experiment, n is the aggregate count of the performance characteristics. Table 5 shows the GRG:

Table 5: Grey relational grade (GRG)

Experimental no.	Grey relational grade
1	0.333333333
2	0.380224381
3	0.412621252
4	0.466834113
5	0.333333333
6	0.411535606
7	0.459174528
8	0.525573514
9	0.333333333
10	0.451605566
11	0.518687344
12	0.601407779
13	0.333333333

14	0.516418137
15	0.598106783
16	0.939578176
17	0.333333333
18	0.400291271
19	0.462972614
20	0.517858205
21	0.333333333
22	0.462572332
23	0.511954362
24	0.599619485
25	0.333333333
26	0.514910967
27	0.600513723
28	0.68379184
29	0.333333333
30	0.639397432
31	0.758057575
32	0.992078166

Optimization of the 8 multiple performance characteristics can be converted into optimization of a single grey relational grade. The mean of the grey relational grade for each level of the considered processing parameters, and the total mean of the grey relational grade is summarized in Table 5. Figure 2 shows the grey relational grade graph, where the dashed line reflects the total mean of the grey relational grade.

The higher value of the grey relational grade represents the stronger relational degree between the reference sequence $x_0(k)$ and the given sequence $x_i(k)$. The reference sequence $x_0(k)$ is the best process response in the experimental layout. The highest value of the grey relational grade means that the corresponding processing parameters is closer to optimal. Meaning, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. The mean of the grey relational grade for each level of factors, and the total mean of the grey relational grade is summarized in Table 6. Figure 2 is the grey relational grade graph, where the dashed line shows the total mean of the grey relational grade.

Table 6: Response table for grey relational grade (GRG)

Processing parameters	Grey relational grade			
	Level 1	Level 2	Level 3	Level 4
Fiber condition	0.4759	0.5298	-	-
Fiber length	0.4134	0.4546	0.5047	0.6388
Fiber loading	0.3333	0.4721	0.5403	0.6658

Total mean grey relational grade= 0.5029

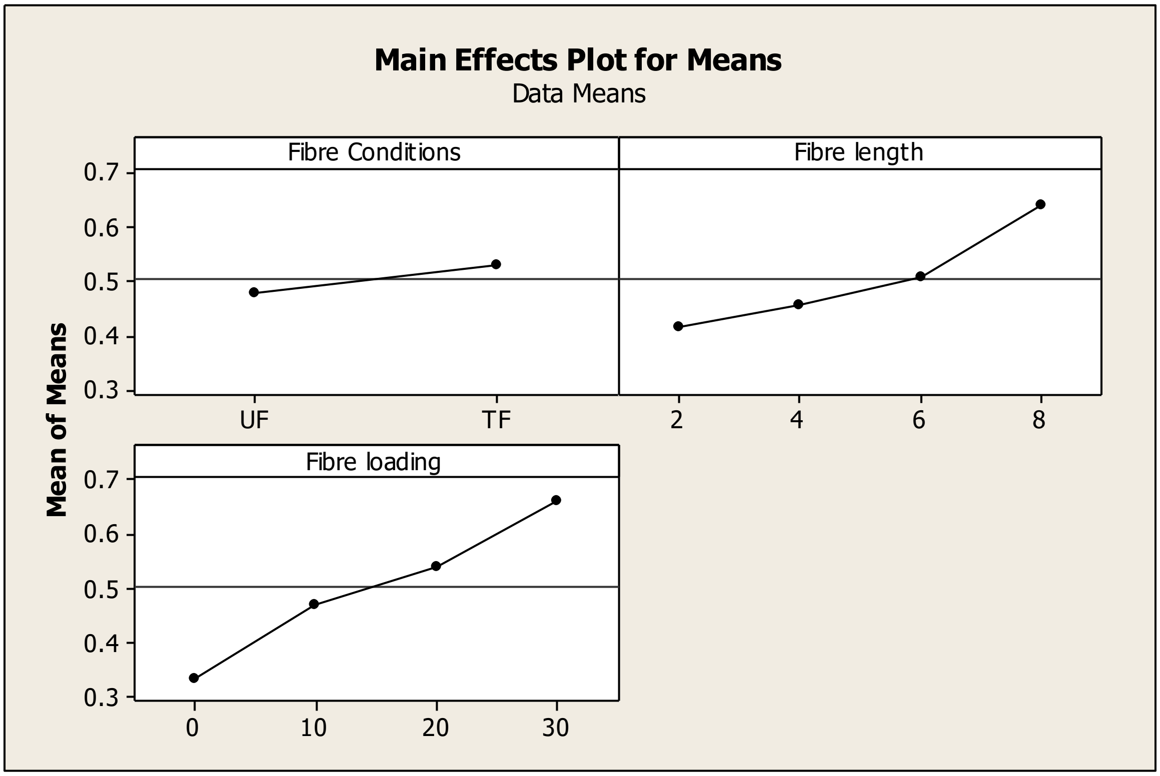

Figure 2: Grey relational grade graph

3.3 Analysis of Variance

The essence of ANOVA is to investigate the factors level combination that significantly affects the overall performance characteristics. This was done by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each factor and the error. First, the total sum of the squared deviations SS_T from the total mean of the grey relational grade γ_m can be calculated using equation (4).

$$SS_T = \sum_j^p (\gamma_j - \gamma_m)^2 \qquad (7)$$

Where p= number of experiments in the orthogonal array, and j= mean of the grey relational grade for the jth experiment. The total sum of the squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_d due to each factor and the sum of the squared error SS_e. The percentage contribution by each factor combination to the total sum of the squared deviations SS_T can be used to evaluate the importance of the factor combination change on the performance characteristics. In addition, the F test, named after Fisher [22] can also be used to determine which factor combination have a significant effect on the performance characteristic. Usually, the change of the factor combination has a significant effect on the performance characteristic when the F value is large. Results of the ANOVA (Table 7) indicate that fiber loading is the most significant factor affecting the multiple performance characteristics, followed by fiber length and treatment. The contribution of error, i.e. noise is insignificant based on the computed % contribution 0f 2.43%

Table 7: ANOVA for grey relational grade (GRG)

Source	DOF	Sum of squares	Mean square	F	% Contribution	Remark
Fiber conditions	1	0.02323	0.023234	3.67	8.93	significant
Fiber length	3	0.23042	0.076806	12.14	29.53	significant
Fiber loading	3	0.46117	0.153724	24.3	59.10	significant
Residual error	24	0.15183	0.006326		2.43	insignificant
Total	31	0.86665	0.26009			

3.4 Confirmation Test

After the determination of optimal level of the factors, the final step is to predict and very the quality characteristics as shown in equation (8): [23]

$$\gamma_{predicted} = \gamma_m + \sum_{i=1}^{q} \gamma_0 - \gamma_m \tag{8}$$

Where γ_0 represents the maximum of average GRG at the optimal level of factors and γ_m represents the mean GRG. The quantity q means the number of factors affecting response values.

From equation (8), the predicted grey relational grade using the optimal factor parameters was computed. From response table in Table 5, using equation (8), the predicted response is 0.8286, compared with the experimental values, which is 0.9921, and it is the experimental number 32.

To investigate closeness of experimental result is to the predicted result, confidence interval (CI) is used in equation (9) (Taguchi, 1989):

$$CI = \sqrt{F_{\propto}(1, f_e) V_e \left[\frac{1}{\eta_{eff}} + \frac{1}{R}\right]} \tag{9}$$

$F_{\propto}(1, f_e)$= F ratio required for α; α= risk; f_e= DOF of error= 24; V_e = variance of error; η_{eff}= effective number of replications, which is the equation (10) below:

$$\eta_{eff} = \frac{N}{1+(total\ DOF\ of\ control\ factors)} \tag{10}$$

R= number of repetitions for confirmation experiment; N+ total number of experiments.

Using the values
V_e= 0.006326; f_e= 24
Total DOF of control factors= 7
R= 1, N= 32
α= 0.5 (95% confidence interval)
$F_{0.5}(1,24)$= 4.26 (tabulated values from the F-Tables)
$\eta_{eff} = \frac{32}{1+7} = 4$
$CI = \sqrt{4.26 \times 0.006326 \left[\frac{1}{4} + \frac{1}{1}\right]} = \pm 0.1835$

The predicted optimal grey relational grade is: $\gamma_{predicted}$= 0.8286
The 95% confidence interval of the predicted optimal grey relational grade as posited by Abifarin [10] is given in equation 11:

$$\gamma_{predicted} - CI < \gamma_{experimental} < \gamma_{predicted} + CI \qquad [11]$$
$$0.6451 < \gamma_{experimental} < 1.0121$$

The experimental grey relational grade, which is for the experimental number 32 was found to be 0.9921. This value is within the confidence interval (95 %) of the predicted optimal grey relational grade.

4.0 Conclusions

The experimental investigations on the analysis of eight multiple performance characteristics (Impact strength, hardness, tensile strength, percentage of elongation, tensile modulus, flexural strength, flexural modulus and water absorption capacity) of coir fiber reinforced recycled HDPE composites have been conducted. From Taguchi grey relational analysis of the experimental results, the following conclusions can be made:

i. Fabrication of coir fiber reinforced recycled HDPE composite with relatively low volume of fibers is feasible by simple hand lay-up technique.
ii. The fiber reinforced HDPE composite has an optimum grey relational grade of 0.8286 and the validated experimental value was within 95% confidence interval.
iii. The optimal control factors (fiber condition, fiber length, fiber loading) are set at (treated fiber (TF), 8mm and 30%wt) or (level 2, level 4, level 4).
iv. Fiber loading is the most significant factor affecting the multiple performance characteristics, followed by fiber length and treatment.
v. The contribution of error, i.e. noise is insignificant based on the computed % contribution 0f 2.43%

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Code availability: Not applicable

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent for publication: Not applicable

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Figures

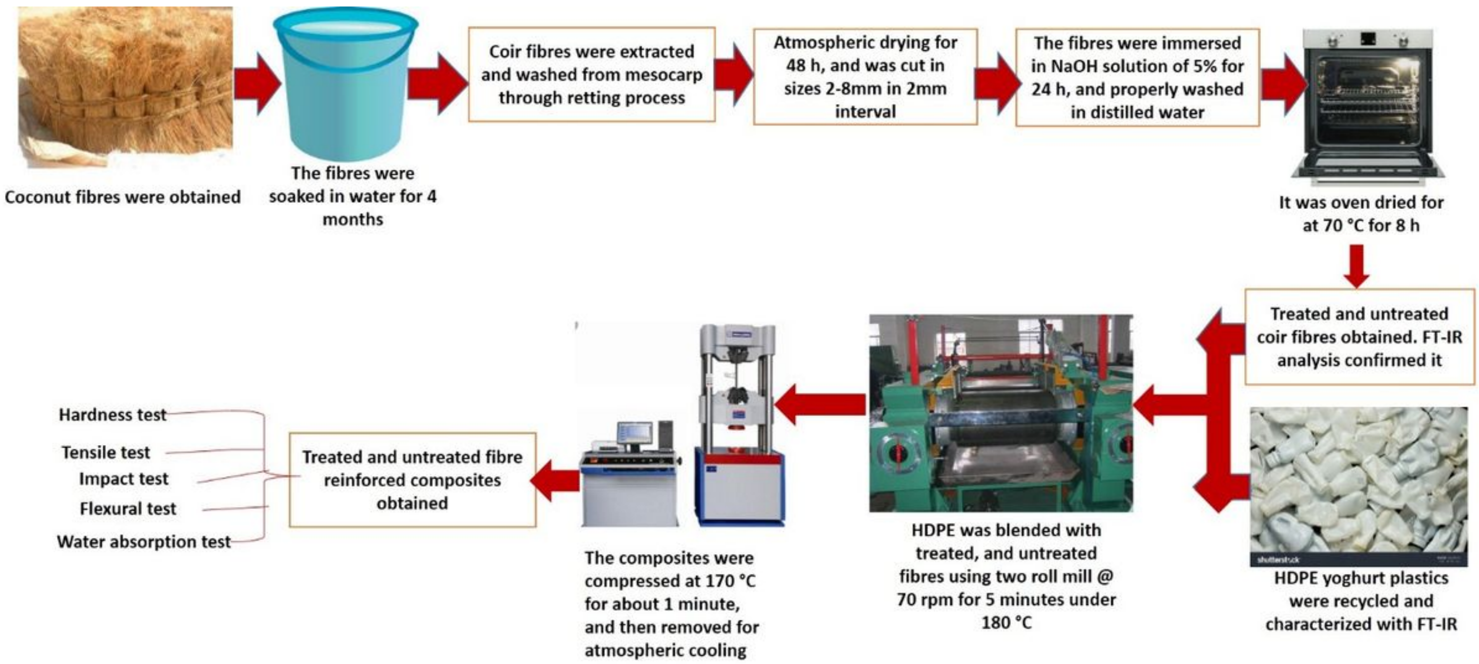

Figure 1

Fabrication of coir fiber reinforced HDPE composite

Figure 2

Grey relational grade graph