Optimizing Agricultural Waste Powder Epoxy Composite for Enhanced Strength Using a Hybrid Taguchi-GRA-PCA Approach

Kumar, Anil
G. B. Pant DSEU Okhla-I Campus

Dahiya, Bhawna
Institute of Environmental Studies, Kurukshetra University

Grover, Dipti
Institute of Environmental Studies, Kurukshetra University

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Optimizing Agricultural Waste Powder Epoxy Composite for Enhanced Strength Using a Hybrid Taguchi-GRA-PCA Approach

Anil Kumar[1,*], Bhawna Dahiya[2], Dipti Grover[2]
[1]G. B. Pant DSEU Okhla-I Campus, New Delhi, 110020, India
[2]Institute of Environmental Studies, Kurukshetra University, Kurukshetra 136119, India

*Author to whom correspondence should be addressed:
E-mail:anilapmae@gmail.com

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Abstract: The characteristics of composite fiberboard can be influenced by several design factors, including the choice and characteristics of the reinforcement material, the matrix material and its proportion, curing conditions, processing methods and moisture content etc. This research specifically focuses on three critical factors: the type of reinforcement material used, the percentage of its weight when combined with epoxy and the curing time required to fabricate the composite fiberboard. The reinforcement materials used include Pistachio shell powder (PSP), Almond shell powder (ASP) and Walnut Shell Powder (WSP). The three levels of weight percentages are 20%, 30%, and 40%. The third factor i.e. curing time also has the three time levels as 24, 36, and 48 hours. Consequently, nine composite fiberboard samples were produced following the configurations specified by the L_9 Orthogonal Array obtained from Taguchi Design. In order to assess the material's properties, the created samples were subjected to Flexural and Impact Strength tests. The results of these tests were then analyzed using Taguchi Analysis to identify the optimal design parameters. To validate the conclusions drawn from the Taguchi analysis, a Principal Component Analysis assisted Grey Relation Analysis was conducted on the output responses. It was observed that the optimal design choice aligns with the use of Reinforcement Material Pistachio Shell Powder at a 30% weight percentage, in conjunction with a curing time of 36 hours for achieving the highest flexural and impact strength.

Keywords: Shell waste; Composite Fiberboard; Flexural and Impact Strength; Taguchi-GRA-PCA;

1. Introduction

Over the past two decades, there has been a significant worldwide trend towards utilizing natural filler materials to create composite materials. Research and development in the realm of sustainable materials have increasingly focused on composite materials derived from agricultural waste products or fruit peels. These materials have gained prominence in today's material science due to their various benefits, including their lightweight properties and resistance to corrosion [1)]. Natural fiber composites are becoming a viable alternative to synthetic composites [2-3).] This shift is attributed to their cost-effectiveness, lightweight nature, exceptional durability, biodegradability, and favorable properties, leading to a rising adoption of natural fibers within the composites sector [4-6)]. The utilization of fruit peel waste holds promise as a reinforcement material for creating composite fiberboards, thereby promoting sustainable resource usage and waste reduction. Citrus peels, which are abundant in natural fibers and bioactive compounds, can be processed and integrated into these fiberboards. The incorporation of citrus peel fibers can improve the board's mechanical properties, while the inherent natural compounds may increase its durability and resistance to decay. By including waste materials like Citrus limetta peel powder in the production of Food Waste filler-based Epoxy Polymer composites, not only does it reduce dependence on petroleum-based Epoxy Polymer products, but it also enhances the potential for environment-friendly disposal of this fruit residue, thus fostering environmentally-conscious manufacturing practices [7-8)]. Composite fiberboards can benefit from the incorporation of pomegranate peels, renowned for their high fiber content and antioxidants. These fibers have the potential to enhance the mechanical characteristics of the board, while the antioxidants might provide protection against environmental wear and tear. Utilizing walnut shell powder in the production of composite fiberboards can lead to the creation of sustainable, lightweight materials that could also have visual appeal, making them suitable for a wide range of applications [9-11)].

While almond production yields numerous byproducts, farmers primarily prioritize the nutritional and commercial aspects of the kernel, leading to limited exploration of almond co-products like almond shells, which make up over 70% of the biomass [12)]. The researchers analyzed the physical composition and chemical characteristics of dry fruit shells such as almond, pistachio and walnut and found that these shells possess the potential for utilization in composite materials and absorbent substances [13-16)]. The most significant flexural strength (35 MPa to 40 MPa) and impact strength (approximately 1780J/m^2) can be obtained by incorporating a volume fraction of almond or walnut shell powder ranging from 20% to 40% in combination with an Epoxy Hybrid Matrix [17-18)].

Researchers have effectively crafted composite materials using Palmyra fruit fiber and Palmyra fiber waste combined with red mud. They observed a substantial improvement in the impact strength, with increases of 39% and 52% for Palmyra fruit fiber and Palmyra fiber waste filled with red mud, respectively, compared to Palmyra/polyester composites. Additionally, the tensile strength demonstrated notable enhancements, showing a 17% and 22% increase for Palmyra fruit fiber and Palmyra fiber waste filled with red mud, respectively, compared to Palmyra/polyester composites. The augmented mechanical performance attributed to the addition of red mud is substantiated by the obtained results [19)]. Furthermore, composites made from natural fibers are environment friendly and can be recycled, making them suitable for recovery and subsequent use [20-21)].

Currently, the predominant method of disposing of used waste is through landfill dumping. However, the rapid development of production, population growth and waste accumulation, have created hazardous conditions for human life. As a result, there is a need to reevaluate production and consumption models, including household waste management. This involves revising management approaches and exploring methods such as processing waste to obtain new materials and useful products and utilizing physical, chemical, and biological means to convert waste into fuel and energy. Some countries, like Sweden, have achieved significant success in this regard, with less than 1% of household waste being sent to landfills [22-23)].

Materials commonly known as bio-composites provide various benefits, including decreased environmental harm, the repurposing of waste substances, and potential biodegradability. Given the current heightened environmental awareness and the demand for sustainable waste management solutions, the effective incorporation of shells from various dried fruits like walnuts, pistachios, and almonds into the production of composite fiberboards proves beneficial due to their numerous advantageous qualities. These include strength, durability, sustainability, cost-effectiveness, and biodegradability. These characteristics collectively render them as valuable assets for a range of industries, including construction, furniture manufacturing, and packaging.

This research aims to tackle the issue of selecting the most appropriate waste material from almond, pistachio, and walnut shells for creating a composite fiberboard with improved flexural and impact strength. This will be achieved by blending the powdered waste shells with epoxy resin using an innovative hybrid approach that combines Taguchi experimental design, Grey Relational Analysis (GRA) and Principal Component Analysis (PCA).

When PCA and GRA are combined, it results in a more effective approach for exploring relationships within the dataset. PCA reduces the dimensionality of the data, simplifying its handling, while GRA provides insights into the correlations among sequences. This integrated approach is especially valuable in situations involving complex and limited data [24-26).]

The impact of various parameters in 'Friction Stir Welding (FSW)' on the electrical conductivity of dissimilar Aluminium-Copper joints was explored by researchers. They noted that all fabricated joints exhibited electrical conductivity at least equivalent to that of aluminum. Utilizing Taguchi analysis, the optimal FSW setup for maximum electrical conductivity was determined to be a shoulder diameter of 18 mm, pin offset of 0.5 mm, welding speed of 63 mm/min, and rotational speed of 900 rpm [27)].

In another study, Taguchi Analysis was employed to identify the optimal combination of process parameters—weight of untreated beads, batch duration, and temperature—for minimizing the weight of expanded beads. The results indicated that the optimal setting within the investigated range was a weight of untreated beads at 17 kg, batch duration of 130 sec, and a temperature of 155◦F, ensuring a stable bead weight [28)].

To validate Taguchi Analysis results, the hybrid technique of GRA assisted with PCA was deemed the most effective and widely adopted method. Numerous researchers are utilizing this hybrid tool to determine optimized design or process parameters.

Additionally, the GRA-PCA based on the Taguchi Method successfully achieved optimal combinations of cutting factors for improved surface finish with an optimum Material Removal Rate in the end milling process of an Aluminum alloy [29)]. By employing the "Hybrid Taguchi/GRA/PCA" method, researchers determined the optimum parameters for end milling as "speed of 900 rpm, feed rate of .04 mm/revolution, depth-of-cut 0.4 mm, and nose radius of 0.6 mm [30)]. Researchers also delved into the effects of cutting force, material removal rate, tool flank wear, and surface roughness during the turning of magnesium alloy using

Taguchi assisted with GRA-PCA. Their observations highlighted that the most influential parameter in this multifaceted process was the 'depth of cut' [31].

Through the integration of these methods, the study seeks to accomplish the following objectives:

1. Create a comprehensive series of experiments using the Taguchi method to explore how certain key factors, like the type of dry fruit shell waste, the percentage of weight involved and the curing time, impact the results.
2. Utilize PCA-assisted GRA to identify the best dry fruit shell waste type that demonstrates the greatest potential for the desired application, taking into account multiple performance criteria simultaneously.

The successful execution of this research will contribute to the efficient utilization of dry fruit shell waste, reducing its environmental impact and promoting sustainability.

2. Methods and Materials

To maintain consistent sourcing conditions, almond, pistachio and walnut shells were obtained from a local market in Delhi, India and subsequently crushed to achieve a powdered texture having approximate size of 0.2 mm to 0.3 mm. Figure 1 shows the different dry fruit shells and the powder produced from them.

Fig. 1- Dry Fruit shells (pistachio, almond and walnut) and their powder

This research focuses on examining the influence of three critical factors: the choice of reinforcement material, the percentage of reinforcement material in combination with epoxy and the curing time for producing composite fiberboard. Each of these factors has been evaluated at three different levels. The reinforcement materials used in this study include pistachio shell powder (PSP), almond shell powder (ASP) and Walnut Shell Powder (WSP). Typically, previous researchers have investigated reinforcement material percentages ranging from 20% to 40%. Therefore, for this study, we have chosen three levels of weight percentages: 20%, 30%, and 40%. The third factor under consideration is the curing time, which has been set at durations of 24, 36 and 48 hours based on the epoxy resin's data sheet. The Table 1 shows the different factors and their corresponding levels.

Table 1. Factors and their corresponding levels

Factor	Level 1	Level 2	Level 3
Reinforcement Materials	Pistachio shell powder (PSP)	Almond shell powder (ASP)	Walnut Shell Powder (WSP)
Weight Percentage	20	30	40
Curing Time	24 Hour	36 Hour	48 Hour

To systematically explore these combinations in a resource-efficient manner, Taguchi Design in conjunction with Minitab 18 has been employed to create an L_9 Orthogonal Array (OA). Table 2 displays the L_9 OA generated through the Taguchi design.

Table 2. L_9 Orthogonal Array (OA)

S. N.	Reinforcement Material	Weight %	Curing Time (H)
1	PSP	20	24
2	PSP	30	36
3	PSP	40	48
4	ASP	20	36
5	ASP	30	48
6	ASP	40	24
7	WSP	20	48
8	WSP	30	24
9	WSP	40	36

Nine composite fiberboard samples were produced using the L_9 Orthogonal Array setups, utilizing the casting method. Novolac resin epoxy was selected for its exceptional resistance to chemicals and stability at high temperatures. To initiate the curing process, a combination of hardener and accelerator was introduced during the creation of the composite panel. The epoxy resin and hardener were mixed in a ratio of 10:1 by weight and thoroughly stirred to prevent the formation of any voids. These well-prepared mixtures, with various configurations in accordance with the Taguchi design, were poured onto clean surfaces while maintaining the desired dimensions in terms of width, length and thickness.

To assess the mechanical properties of the manufactured composite, the following tests were conducted on the different specimens.

1. Flexural Strength Test
2. Impact Strength Test

2.1 Flexural Strength Test

The test procedure assesses the flexural characteristics of the composite materials, adhering to the standards outlined in ASTM D790. The flexural testing was carried out using a Universal Testing Machine (UTM-D2-SERVO, 500 N) applying a consistent loading rate of 2 millimeters per minute. The specimen was prepared to have dimensions measuring 191x12 mm^2 with a depth of 12 mm. The configuration for conducting this experiment is illustrated in Fig. 2.

Fig 2: Flexural Strength Test Setup

The flexural strength for all nine specimens has been computed and is presented in the tabular format shown in Table 3 below.

Table 3. Flexural Strength for 9 Specimens

Configuration No.	Flexural Strength (MPa)
1	41.72
2	45.38
3	38.63
4	42.65
5	38.85
6	34.57
7	29.17
8	38.25
9	32.53

Figure 3 shows the behavior of different samples under 3PBT. While testing various specimens, it was noted that the occurrence of voids within distinct fiberboards led to a decline in mechanical integrity and an elevated vulnerability to failure. These voids caused insufficient load distribution, consequently diminishing the overall flexural strength of the composite. To enhance the composite's flexural strength, it is advisable to minimize voids and improve the bonding between the walnut shell particles and the polymer matrix.

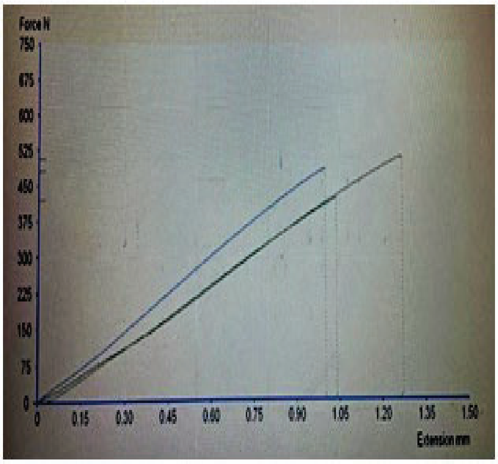

Fig 3: Behavior of test specimen under 3PBT

2.2 Impact Strength Test

The Charpy Impact Strength Test (ASTM D256) was conducted using a Charpy Impact Testing Machine to determine the impact resistance of various samples. Charpy Impact Testing Machine and test setup has been illustrated in Fig. 4.

Fig 4: Impact Strength Test Setup

The impact strength for all nine specimens has been computed and is presented in the tabular format shown in Table 4 below.

Table 4. Impact Strength for 9 Specimens

Configuration No.	Impact Strength (KJ/m^2)
1	3.32
2	4.51
3	2.84
4	1.65

5	1.74
6	1.57
7	1.69
8	1.97
9	1.86

3. Results and Discussion

3.1 Taguchi Analysis

The main objective of Taguchi Analysis is to enhance processes, products and systems by pinpointing the key factors that exert the most substantial influence on performance and quality. The values obtained for the two distinct responses have been matched with the various arrangements found in the L_9 Orthogonal Array, as depicted in Table 5.

Table 5. Different configurations and their responses

S. N.	Reinf. Mat.	Weight %	Curing Time (H)	FS (MPa)	IS (KJ/m^2)
1	PSP	20	24	41.72	3.32
2	PSP	30	36	45.38	4.51
3	PSP	40	48	38.63	2.84
4	ASP	20	36	42.65	1.65
5	ASP	30	48	38.85	1.74
6	ASP	40	24	34.57	1.57
7	WSP	20	48	29.17	1.69
8	WSP	30	24	38.25	1.97
9	WSP	40	36	32.53	1.86

a. Taguchi Analysis for Flexural Strength

To determine the most effective dry fruit shell waste powder, Taguchi analysis was conducted using the calculated flexural strength data. Since the primary criterion for designing a composite fiberboard is achieving greater flexural strength, the "Larger is Better" criterion was employed to identify the superior dry fruit shell waste powder as a reinforcement material. Table 6 displays the Response Table, which contains Signal to Noise Ratios (SNR) obtained following the Taguchi analysis.

Table 6. Response Table for SNR (Larger is better)

Level	RM	WP	CT
1	32.43	31.43	31.61
2	31.72	32.19	31.99
3	30.40	30.92	30.94
Delta	2.03	1.27	1.05

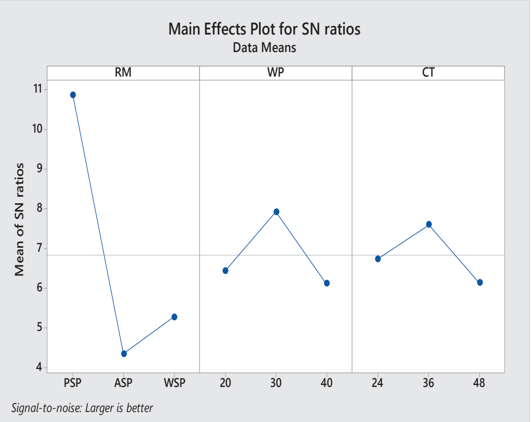

Fig 5: Main Effect plot for Flexural Strength

According to Fig. 5, the maximum Flexural strength was attained with the configuration involving pistachio shell powder, a weight percentage of 30 and a curing time of 36 hours.

b. Taguchi Analysis for Impact Strength

Taguchi analysis was employed to select the most effective agricultural waste powder for strengthening composite fiberboards, with a specific emphasis on determining the impact strength of nine distinct configurations. The key objective in designing these composite fiberboards was to maximize impact strength, and thus the "Larger is Better" criterion was chosen. This approach was intended to pinpoint the best agricultural waste powder for enhancing the board's performance. The outcomes of the Taguchi analysis are summarized in Table 7, which presents the Response Table for Signal to Noise Ratios, revealing the findings of the Taguchi analysis.

Table 7: Response Table for SNR (Larger is better)

Level	RM	WP	CT
1	10.858	6.443	6.743
2	4.360	7.928	7.608
3	5.279	6.125	6.145
Delta	6.498	1.803	1.463

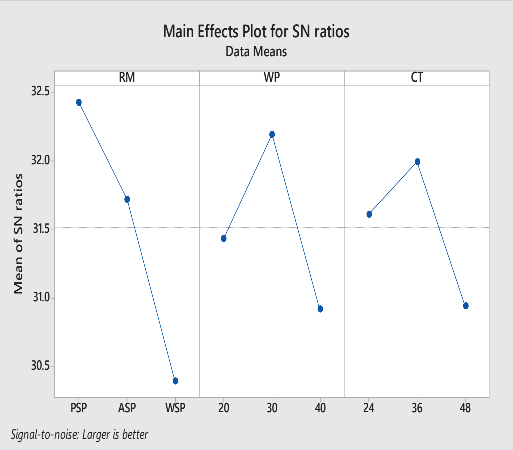

Fig 6: Main Effect plot for Impact Strength

According to Fig. 6, the maximum Impact strength was attained with the configuration involving pistachio shell powder, a weight percentage of 30 and a curing time of 36 hours.

c. Taguchi Analysis for Flexural Strength and Impact Strength Taken Together

Another Taguchi Analysis was conducted, this time considering both response variables simultaneously. Table 8 displays the Response Table for Signal to Noise Ratios for both responses combined under the "Larger is Better" criterion. This analysis aimed to evaluate the performance of the composite fiberboards with respect to both responses when assessed together.

Table 8. Response Table for SNR (Larger is better)

Level	RM	WP	CT
1	13.837	9.438	9.738
2	7.362	10.917	10.597
3	8.276	9.120	9.140
Delta	6.475	1.798	1.457

As shown in Fig. 7, the most favorable combination, which yields the highest values for both response variables, entails utilizing pistachio shell powder at a weight percentage of 30% and subjecting it to a curing duration of 36 hours.

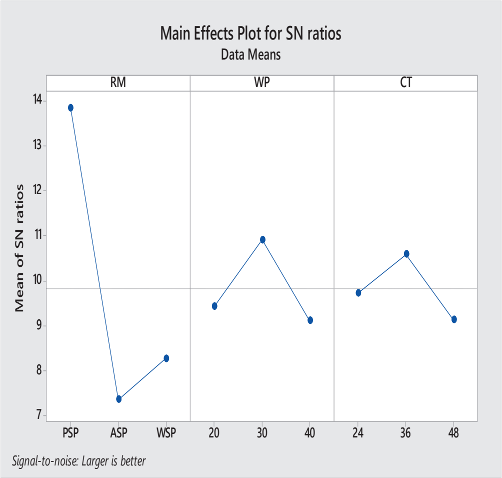

Fig 7: Main Effect plot for S/N Ratios for Impact and Flexural Strength taken together

The Taguchi analysis revealed that the optimal mechanical properties are achieved when a combination of pistachio shell powder at a weight percentage of 30% and curing for 36 hours has been employed.

3.2 PCA Assisted GRA

Taguchi's approach is effective when determining the optimal settings for process variables that affect a single outcome. However, when it comes to optimizing multiple outcomes, the commonly used method is Grey Relational Analysis (GRA). To validate the results obtained from the Taguchi analysis in this study, GRA was employed. GRA involves the process of normalizing values to calculate "Grey Relational Coefficients (GRC)" and "Grey Relation Grade (GRG). In this research, both Flexural and Impact strength responses, both falling into the "Larger-is-better" category, were selected for analysis. Initially, values for both responses were normalized, and then Deviation Sequences were computed, as shown in Table 9.

Table 9. Responses and their Normalized value

Responses			**Normalized Values**	
S. N.	**FS**	**IS**	**FS**	**IS**
1	41.72	3.32	0.77	0.60
2	45.38	4.51	1.00	1.00
3	38.63	2.84	0.58	0.43
4	42.65	1.65	0.83	0.03
5	38.85	1.74	0.60	0.06
6	34.57	1.57	0.33	0.00
7	29.17	1.69	0.00	0.04
8	38.25	1.97	0.56	0.14
9	32.53	1.86	0.21	0.10

After calculating the deviation sequences, the GR coefficients for the two responses were established and these coefficients are displayed in Table 10.

Table 10. Deviation Sequences and Grey Relational Coefficients (GRC)

S. N.	**Deviation Sequences**		**Grey Relational Coefficients**	
	FS	**IS**	**FS**	**IS**
1	0.23	0.40	0.69	0.55
2	0.00	0.00	1.00	1.00
3	0.42	0.57	0.55	0.47
4	0.17	0.97	0.75	0.34
5	0.40	0.94	0.55	0.35
6	0.67	1.00	0.43	0.33
7	1.00	0.96	0.33	0.34
8	0.44	0.86	0.53	0.37
9	0.79	0.90	0.39	0.36

Principal Component Analysis (PCA) has been incorporated into Grey Relational Analysis (GRA) to assess the significance of each performance attribute. The weighted values for these attributes were determined using PCA. The different performance attributes that exhibit Grey Relational Coefficients (GRCs) were input into Minitab 18. Subsequently, Minitab 18 generated Eigen-values, as documented in Table 11. Additionally, the corresponding Eigen-vectors for these Eigen-values were generated through MINITAB and are presented in

Table 12. By utilizing these Eigen-vectors for Principal Components, the contribution of each performance attribute was calculated, as elaborated in Table 13. The individual contributions of performance attributes, such as Flexural and Impact Strength, are detailed in Table 13.

Table 11. Eigen analysis of the Correlation Matrix

Eigen value	1.6562	0.3438
Proportion	0.828	0.172
Cumulative	0.828	1.000

Table 12. Eigen vectors

Variable	**PC1**	**PC2**
TS	0.707	0.707
FS	0.707	-0.707

Table 13. Contribution of the used performance characteristic for the principal components

Performance characteristic	**Weighted value**
Impact Strength	$(0.707)^2 = .5$
Flexural Strength	$(0.707)^2 = .5$

As shown in Table 13, we determined the Grey Relation Grades (GR Grades) by utilizing Principal Component Analysis (PCA) in conjunction with the weighted values assigned to all the responses. To clarify this process further, we offer a demonstration of how we calculated the Grey Relation Grade (GRG) for Configuration No. 1 below:

$$\boldsymbol{(GRG)=1(k) = (1/2*(0.5*FS+0.5*IS))}$$

Table 14. Grey relation grades (GRG)

PCA assisted GR Grades
0.078
0.125
0.063
0.068
0.056
0.048
0.042
0.056
0.046

In order to identify the most effective settings for different process factors, we evaluated the average GRG (Grey Relation Grade) value for each level of these factors, and we chose the highest GRG value for each factor. The bold and darkened values in Table 14 represent the highest GRG values among the various levels of each process factor. These specific values are associated with the following optimal response characteristics: Reinforcement Material PSP, with a weight percentage of 30%, and a curing time of 36 hours.

Table 15. Grey Relation Grade Values Analogous to Different Levels of Input Process Factors

Level	**Reinforcement Material**	**Weight %**	**Curing Time**
1	**0.08867**	0.06267	0.06067
2	0.05733	**0.079**	**0.07967**
3	0.048	0.05233	0.05367

The GRA confirms that the optimum design is available for Reinforcement Material PSP, Weight % of 30% and Curing Time 36 Hours.

3.3 Confirmatory Test

Table 15 clearly illustrates that the results obtained from the Grey Relational Analysis (GRA) of response characteristics fully corroborate the conclusions drawn from the Taguchi Analysis. Additionally, it was observed that the optimal design choice aligns with the use of Reinforcement Material PSP at a 30% weight percentage, in conjunction with a curing time of 36 hours.

Table 16. Comparison of the results of Taguchi and GRA

Input Factors	**Taguchi Levels**	**GRA Levels**	**Value**
Reinforcement Material	1	1	PSP
Weight %	2	2	30%
Curing Time	2	2	36 Hr.

4. Conclusion

In conclusion, the objective of this research was to examine the impact of three crucial variables on composite fiberboard production: the choice of reinforcement material, its weight percentage when combined with epoxy and the curing time. The investigation revealed that the most effective combination involves utilizing Pistachio Shell Powder as the reinforcement material at a 30% weight percentage, coupled with a curing time of 36 hours. This particular set of factors resulted in composite fiberboards exhibiting exceptional mechanical properties, as evidenced by the Impact and Flexural Strength tests.

This study not only successfully employed the Taguchi Design methodology to explore various factors and their interactions but also validated the optimal design through additional analysis techniques such as GRA-PCA. The recommended configuration underscores the significance of Pistachio Shell Powder as the reinforcement material, along with the specific weight percentage and curing time, in achieving composite fiberboards with outstanding mechanical attributes. These findings contribute to advancing manufacturing methods for composite materials and offer valuable insights for industries aiming to improve the performance and durability of fiberboard-based products.

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Nomenclature

PSP	Pistachio Shell Powder
ASP	Almond Shell Powder
WSP	Walnut shell powder
GRA	Grey Relation Analysis
PCA	Principal Component Analysis
SNR	Signal to Noise Ratio
L_9 OA	L_9 Orthogonal Array

References

1) A. Kumar, A.K. Chanda, and S. Angra, “Numerical modelling of a composite sandwich structure having non metallic honeycomb core,” Evergreen, 8 (4) 759–767 (2021). doi:10.5109/4742119.
2) R.B. Yusoff, H. Takagi, and A.N. Nakagaito, “Impact and flexural properties of polylactic acid-based hybrid green composites reinforced by kenaf, bamboo and coir fibers,” Ind Crops Prod, 94 562–573 (2016). doi:10.1016/j.indcrop.2016.09.017.
3) M. Faizi, M. Abdul Majid, S. Bmt, S. Basah, E. Cheng, M. Afendi, K. Wan, and D. Hazry, “An overview of the Oil Palm Empty Fruit Bunch (OPEFB) potential as reinforcing fibre in polymer composite for energy absorption applications,” n.d.
4) A. C. Milanese, M.O.H. Cioffi, and H.J.C. Voorwald, “Thermal and mechanical behaviour of sisal/phenolic composites,” Compos B Eng, 43 (7) 2843–2850 (2012). doi:10.1016/j.compositesb.2012.04.048.
5) A. Porras, and A. Maranon, “Development and characterization of a laminate composite material from polylactic acid (pla) and woven bamboo fabric,” Compos B Eng, 43 (7) 2782–2788 (2012). doi:10.1016/j.compositesb.2012.04.039.
6) A.C. Opia, M.K.A. Hamid, S. Syahrullail, A.I. Ali, C.N. Johnson, I. Veza, M.I. Izmi, C.D.Z. Hilmi, and A.B. Abd Rahim, “Tribological behavior of organic anti-wear and friction reducing additive of zddp under sliding condition: synergism and antagonism effect,” Evergreen, 9 (2) 246–253 (2022). doi:10.5109/4793628.
7) M. K. Gupta, V. Singhal, and N. S. Rajput, “Applications and challenges of carbon-fibres reinforced composites: a review,” Evergreen, 9 (3) 682–693 (2022). doi:10.5109/4843099.
8) H. Sharma, I. Singh, and J.P. Misra, “Mechanical and thermal behaviour of food waste (citrus limetta peel) fillers–based novel epoxy composites,” Polymers and Polymer Composites, 27 (9) 527–535 (2019). doi:10.1177/0967391119851012.
9) M. Mittal, K. Phutela and Rajiv Chaudhary, “Influence of Walnut (Juglans L.) Shell Particles Addition on the Mechanical Properties of Epoxy Composites,” Applied Mechanics and Materials, 903 117-124 (2021).
10) N. M.Moustafa, K. A. Mohammed, E. S. Al-Ameen, A. A. F. Ogaili, and M. N. M. Al-Sabbagh, “Mechanical and tribological properties of walnut/polypropylene natural composites,”Journal of Mechanical Engineering Development Research, 43 (4) 372-380 (2020).
11) V. K. Singh, “Mechanical behavior of walnut shell particles reinforced bio-composite,” Science and engineering of composite materials, 22(4) 383-390 (2015).
12) R. Melhaoui, Y. Miyah, S. Kodad, N. Houmy, M. Addi, M., Abid, A. Mihamou, H. Serghini-Caid, S. Lairini, N. Tijani and C. Hano, “On the suitability of almond shells for the manufacture of a natural low-cost bioadsorbent to remove brilliant green: kinetics and equilibrium isotherms study,” The Scientific World Journal, 2021. https://doi.org/10.1155/2021/6659902.
13) X. Li, Y. Liu, J. Hao, and W. Wang, “Study of almond shell characteristics,” Materials, 11, 1782 (2018). doi:10.3390/ma11091782.
14) A. Mohamad, A. Erkliğ and K. Albu-khaleefah, "Effect of pistachio shell particle content on the mechanical properties of polymer composite," Arabian Journal for Science and Engineering, 43 4689-4696 (2018).
15) S. Sajith, V. Arumugam, and H.N. Dhakal, “Comparison on mechanical properties of lignocellulosic flour epoxy composites prepared by using coconut shell, rice husk and teakwood as fillers,” Polym Test, 58 60–69 (2017). doi:10.1016/j.polymertesting.2016.12.015.
16) K.G. Satyanarayana, K. Sukumaran, R.S. Mukherjee, C. Pavithran, and S.G.K. Piuai, “Natural Fibre-Polymer Composites,” 1990.
17) K. Yesuraj, K., Pazhanivel, S. P. Srinivasan, V. Santhanam, and K. Muruganantham, “Static investigation of almond shell particulate reinforced aquilaria agallocha roxb blended epoxy hybrid matrix composite,” Digest Journal of Nanomaterials and Biostructures, 16 (2) 359-365 (2021).
18) P. P. Patil and R Taluja,“ Experimental investigation of Pistachio shell concentrations on the Mechanical performance of hemp fiber Reinforced Polyester Composites,” Webology, 18 (3) 1401-1409 (2021).
19) V.A. Prabu, V. Manikandan, R. Venkatesh, P. Vignesh, S. Vignesh, K. Siva Sankar, P. Sripathy, and E. Subburaj, “Influence of redmud filler on palmyra fruit and palmyra fiber waste reinforced polyester composite: hardness, Impact and impact

studies," Materials Physics and Mechanics, 24 (1) 41–49 (2015).

20) K.R. Sumesh, V. Kavimani, G. Rajeshkumar, S. Indran, and A. Khan, "Mechanical, water absorption and wear characteristics of novel polymeric composites: impact of hybrid natural fibers and oil cake filler addition," Journal of Industrial Textiles, 51 (4) 5910S-5937S (2022). doi:10.1177/1528083720971344.

21) M. Bagci, "Determination of solid particle erosion with taguchi optimization approach of hybrid composite systems," Tribol Int, 94 336–345 (2016). doi:10.1016/j.triboint.2015.09.032.

22) C.M. Galanakis, "Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications," Trends Food Sci Technol, 26 (2) 68–87 (2012). doi:10.1016/j.tifs.2012.03.003.

23) M.R. Hamidian, P. Shafigh, M.Z. Jumaat, U.J. Alengaram, and N.H.R. Sulong, "A new sustainable composite column using an agricultural solid waste as aggregate," J Clean Prod, 129 282–291 (2016). doi:10.1016/j.jclepro.2016.04.072.

24) A. Kumar, A. K. Chanda, and S. Angra, "Optimization of stiffness properties of composite sandwich using hybrid Taguchi-GRA-PCA," Evergreen, 8 (2) 310–317 (2021). doi:10.5109/4480708.

25) A. Kumar and S. Singh, "Fabrication and Optimization of Wear Behaviour of Citrus Limetta Peel Particulate Composite using Hybrid Taguchi-GRA-PCA," Evergreen, 10 (3) 1323-1329, (2023). doi.org/10.5109/7151679

26) R. Kumar, K. Kumar, and S. Bhowmik, "Optimization of mechanical properties of epoxy based wood dust reinforced green composite using taguchi method," Procedia Materials Science, 5, 688–696 (2014). doi:10.1016/j.mspro.2014.07.316.

27) N. Sharma, Z. A. Khan, A. N. Siddiquee, S. K . Shihab, and M. A. Wahid "Effect of process parameters on microstructure and electrical conductivity during FSW of Al-6101 and Pure Copper" *Materials Research Express*, *5*(4) (2018). https://doi.org/10.1088/2053-1591/aabbe0.

28) 28. S. I. Ishrat, Z. A. Khan, A. N. Siddiquee, I. A. Badruddin, A. Algahtani, S. Javaid, and R. Gupta, "Optimising parameters for expanded polystyrene based pod production using Taguchi method," Mathematics, 7(9), 1-17 (2019). https://doi.org/10.3390/math7090847.

29) 29. S. K. M. Johny, C. R. S. Sai, V. R. Rao and B. G. Singh, "Multi-response optimization of aluminium alloy using GRA-PCA by employing Taguchi method," International Research Journal of Engineering and Technology, 3 (01) 680-686 (2016).

30) P. Umamaheswarrao, D. R. Raju, K. Suman, B. R. Sankar, "Multi objective optimization of process parameters for hard turning of AISI 52100 steel using Hybrid GRA-PCA," *Procedia Computer Science*, *133*, 703–710 (2018). https://doi.org/10.1016/j.procs.2018.07.129

31) R. Viswanathan, S. Ramesh, S. Maniraj, and V. Subburam, "Measurement and multi-response optimization of turning parameters for magnesium alloy using hybrid combination of Taguchi-GRA-PCAtechnique",Measurement, 159,107800(2020).https://doi.org/10.1016/j.measurement.2020.107800.