JJMIE

Volume 15, Number 5, December. 2021
ISSN 1995-6665
Pages 411 - 417

Jordan Journal of Mechanical and Industrial Engineering

Improving Mechanical Properties of Rice Husk and Straw Fiber Reinforced Polymer Composite through Reinforcement Optimization

Sachin G Ghalme

Mechanical Engineering Department, Sandip Inst. of Tech. and Research Centre, Nashik (MS), India

Received May 1 2021 *Accepted October 6 2021*

Abstract

The generation of lignocellulosic agriculture waste and the residue is unavoidable, and disposal of the same with burning or burying creates environmental issues. In recent years the scientific community is continuously looking for sustainable development using natural resources for development. Rice husk (RH) and straw (RS) are already proposed as natural fiber reinforcing materials for natural fiber reinforced polymer composite (NFRPC). In this article, an attempt has been made to obtain the optimized proportion of rice husk and straw reinforcement in bio epoxy resin for the development of rice husk and straw fiber-reinforced hybrid composite with improved mechanical properties. The grey relational analysis (GRA) methodology is implemented to obtain the optimized proportion of RH and RS for maximization of tensile and flexural strength of polymer composite simultaneously. The experimental and grey relational analysis result presents the addition of 05 and 08 wt% of RS and RH fiber respectively in bio epoxy resin presents rice straw and husk reinforced polymer composite with improved tensile and flexural strength simultaneously.

Keywords: Natural fiber reinforced polymer composite (NFRPC), rice husk (RH), rice straw (RS), mechanical properties, grey relational analysis (GRA);

1. Introduction

Polymer composite has presented itself as advanced materials to satisfy the demand for the development of advanced engineered materials for various applications. Polymer composite shows different chemical constituents due to the continuous matrix phase and various reinforcements. Since composites are fabricated with two or more dissimilar materials, after utilization both materials cannot be easily recycled. They need to be dump in landfills or incinerated. Both these disposal alternatives are expensive, wasteful, and contribute to environmental pollution. The growing concern about the environmental issues and development of advanced materials has forced us to utilize the natural resources for the development of fiber polymer composite, which is environmentally friendly and does not cause any harm in terms of pollution and decompose effortlessly [1]. The requirement for sustainable development attracted the attention of the research community to utilize natural fibers as reinforcing material for polymer composites. Natural fibers are thread-like naturally available structures with a high aspect ratio. They are classified based on their source like vegetable fibers (abaca), animal fibers (silk) and mineral fibers (asbestos) [2]. The vegetable or plant fibers such as rice, groundnut, banana, coir, pineapple leaf, oil palm, flax, jute and many more are nowadays employed as natural reinforcement in polymer composite to replace synthetic fibers such as glass, carbon and Kevlar due to their biodegradability and low cost [3-5]. Plant fibers mainly consist of cellulose. The various examples are linen, jute, cotton, flax, sisal and hemp. These fibers are extracted from the fruits, seeds, leaves, stem and skin of plants. Based on this they are categorized as leaf fiber (collected from leaves, e.g. sisal and agave), seed fiber (collected from seeds or seed cases, e.g. cotton and kapok), bast fiber or skin fiber (collected from the skin or bast surrounding the stem, e.g. jute, kenaf, hemp, ramie, rattan, soyabean, vine and banana fibers), fruit fiber (collected from the fruit of the plant, e.g. coconut, coir fiber) and stalk fiber (stalks of the plant, e.g. straws of wheat, rice, barley and other crops including bamboo, grass and tree wood).

Natural fibers present significant mechanical properties, and in addition to this, they are renewable, eco-friendly, easy to be availabile, renewable, low price and density. They are alternatives to the synthetic fiber components such as glass, carbon used in the fabrication of polymer matrix composites and are significantly susceptible to microorganisms [6-8]. There are enormous applications of NFRP composites in the automotive and aerospace interior, packaging, consumer products, defence, civil, marine, sports and textile industries due to their higher specific properties along with sustainable development and disadvantages associated with the synthetic raw materials [9-12].

Rice is a substantial food crop in the agriculture sector belonging to cereal grains like wheat, barley, oat, and about 1% of the earth's surface comes under this food crop [13-

* Corresponding author e-mail: sachinghalme@hotmail.com.

15]. The rice husk and straw shown in Figure 1 are two major agricultural wastes generate during rice production.

(a) (b)

Figure 1. (a) Rice straw, (b) Rice husk

Rice straw belongs to the stalk fiber and covers a substantial portion of rice yield and is separated from rice using a machine or manually in the field itself. The vital application of rice straw is used as reinforcement for the structural board as it shows good sound-absorbing property [16]. Rice straw also contains cellulose, a potential material for composite. Rice husk is a secondary byproduct during the production of rice grain. It is nonedible hard protecting encapsulation of the rice grain, and for every 1000 Kg of rice paddy, about 20-30% husk is generated [13-18]. Rice husk is abrasive in nature along with low density, toughness and resistance to weathering. It is used as filler in construction and insulation materials, fuel and as composite for manufacturing of bricks, panels, decks, and window and door frames [19].

The main limiting factor associated with the application of NFRPC as reinforcement or filler is their dimensional instability due to their hydrophilic characteristic and poor water resistance. Availability of hydroxyl in cellulose is the main cause for swelling of NFRPCs as it has a tendency of bonding with hydrogen in water [20]. Several authors have studied the mechanical properties of rice straw fiber-reinforced polymer composite [21, 22].

Hybrid composites apply more than one reinforcement or matrix to generate composite with improved properties. M. A. Abd El-baky [23] evaluated the tensile and flexural properties of jute-glass-carbon fiber reinforced epoxy hybrid composite and presented that hybridization of process improved the tensile and flexural properties of jute reinforced composite. Pakravan et al. [24] blended RH with polyvinyl alcohol (PVA) fibers and used it as reinforcement for cementitious hybrid composite. They found improved mechanical properties along with the reduced density of composite due to hybridization. In another study, Jawad K. Oleiwi et al. [25] evaluated the flexural and impact properties of hybrid composite reinforced with bamboo and rice husk particles. They found that flexural and impact strength improved with small particle size and reinforcement concentration.

In earlier studies related to the RH and RS, the effect of individual reinforcement has been considered on mechanical properties. No study deals with hybridization. Optimization of process parameters or during product development help us to achieve a balance between input and output with aim of maximization or minimization of desired output [26,27]. The effect of combined RH and RS in epoxy resin is not evaluated in earlier studies. The current study is aimed at obtaining the optimum proportion of RH and RS in bio epoxy resin for maximizing the tensile and flexural strength of the NFRPC.

2. Materials and Method

2.1. Materials

Rice straws were collected from the local agriculture fields near our campus in Trimbakeshwar (Nashik) region, and husk was collected from local rice mills.

The matrix material used in this investigation was bio epoxy resin Grade Ly-556 and Hardener Hy-951, supplied by Lab Chemicals.

2.2. Methodology: Grey Relational Analysis (GRA)

To complete the systematic and statistical analysis of the experimental results, the experiments were planned and results were analysed with grey relational analysis (GRA). The GRA is a statistical technique implemented to optimize the multi-objective functions [28-31].

Normalization of Data

The collected raw experimental data is normalized into 0 or 1, with two criteria wise lower is better (LB) and higher is better (HB). A LB criterion is used to normalize data when the objective function is to minimize. Equation 1 is used for LB criteria. A HB criterion is used to normalize data when the objective function is to maximize. Equation 2 is used for HB criteria.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{1}$$

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{2}$$

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 k^{th} response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response. $i = 1, 2, 3\ldots$ the number of experiments and $k = 1, 2, 3\ldots$ the number of responses.

In this study, I was expecting to maximize both tensile strength and flexural strength. So, Equation 2 is used to normalize experimental data.

Calculation of Grey Relational Coefficient (GRC)

GRC is calculated to determine the relation between ideal and actual normalized experimental data. GRC (ξ) is calculated using equation 3. A relation is established between actual values and normalized values of tensile strength and flexural strength using Equation 3.

$$\xi = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{oi}(k) + \psi\Delta_{\max}} \tag{3}$$

Where,

$$\Delta_{oi}(k) = \left\| x_o(k) - x_i(k) \right\|$$

The difference of the absolute value of $x_0(k)$ and $x_i(k)$; ψ is the distinguishing coefficient; $0 < \psi < 1$, Δ_{min} is the smallest value of $\Delta_{oi}(k)$ and Δ_{max} is the largest value of $\Delta_{0i}(k)$.

Calculation of Grey Relational Grade (GRG)

The analysis of multiple outputs characteristics is based on grey relational grade. This will convert multiple responses into a single numerical value. The GRG (γ) is an average sum of GRC and calculated using Equation 4. Its value lies between 0 and 1.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (4)$$

Where n is a number of process responses. In this work, tensile strength and flexural strength are two responses.

3. Experimental Work

3.1. Sample preparation

At first, the RH and RS fibers were ground and were washed thoroughly with water. After that, it was dried under direct sunlight for 8 hours. Then, RH and RS fibers were soaked separately in NaOH solution (1% NaOH powder & 99% distilled water) for 3 hours. After soaking, it was washed again with running water and dried under shade for another 4 hours to remove residual NaOH. Soaking of RH and RS in NaOH solution results in the removal of the natural fats and waxes from the surface. Thus, the removal of fats and waxes from the surface exposes it readily to available chemical reactive groups for interaction with the matrix material. The removal of surface impurities enhances surface roughness owing to the treatment of RH and RS with NaOH. Surface roughness makes the wetting (mechanical interlocking) favorable and leads to improved mechanical properties.

The various proportions of RH, RS and Resin selected are presented in Table 1, as shown above. To achieve the proper curing epoxy resin and hardener were added in the 10:1 proportion. The measured quantity of Resin & Hardener (10:1) was poured into the beaker and stirred well for 25 minutes to make a homogeneous mixture.

Then calculated quantities of RH and RS fibers were then mixed with epoxy & the mixture is stirred for another 30 minutes.

Thereafter, the obtained mixture was poured into metal moulds with different dimensions as per the requirement of the test standards. Silicon releasing agent was spread over the mould for easy removal of cured samples. The sample is then allowed to solidify for 12 hours.

3.2. Mechanical Testing

Tensile Test

Tensile testing is used to measure the force required to break a polymer composite specimen and the extent to which the specimen stretches or elongates to that breaking point. Tensile tests produce a stress-strain diagram, which is used to determine tensile modulus. The data is often used to specify a material to design parts to withstand application force and as a quality control check of materials.

The tensile test was conducted according to the ASTM D3039. The most common specimen for ASTM D3039 is a constant rectangular cross-section, 25 mm wide and 250 mm long, 4-5mm thick. Figure 2 shows the specimen used for the tensile test.

Figure 2. Tensile test specimen

During testing, the specimens were fixed in the grips of a Universal Test Machine. For ASTM D3039, the test speed can be determined by the material specification or time to failure (1 to 10 minutes). A typical test speed for standard test specimens is 2 mm/min (0.05 in/min). An extensometer or strain gauge is used to determine elongation and tensile modulus. The tensile load was applied until the final failure of the specimen. Tensile test data is helpful for the selection of material in the tensile application. Figure 3 shows the tensile test setup used for experimentation.

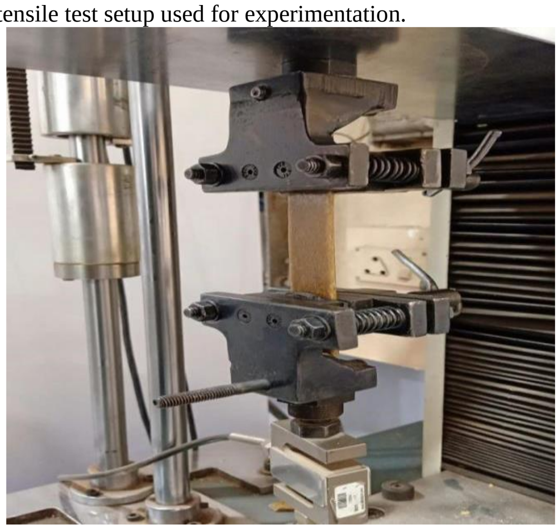

Figure 3. Tensile test setup

Flexural Test

The flexural test measures the force required to bend a beam under three-point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed. The test was conducted according to ASTM D790. A variety of specimen shapes can be used for this test, but the most commonly used specimen size for ASTM is 3.2mm x 12.7mm x 125mm (0.125" x 0.5" x 5.0") and for ISO is 10mm x 4mm x 80mm. Figure 4 shows the specimen used for flexural testing.

Table 1. Compositional proportion

	Wt %														
RS	5	5	5	5	5	8	8	8	8	8	11	11	11	11	11
RH	5	8	11	14	17	5	8	11	14	17	5	8	11	14	17
Resin	90	87	84	81	78	87	84	81	78	75	84	81	78	75	72

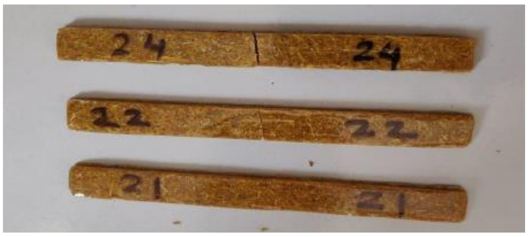

Figure 4. Flexural test specimen

During testing, the specimen lies on a support span, and the load is applied to the center by the loading nose producing three-point bending at a specified rate. The test parameters are the support span, the speed of the loading, and the maximum deflection for the test. These parameters are based on the test specimen thickness and are defined differently by ASTM and ISO. For ASTM D790, the test is stopped when the specimen reaches 5% deflection or the specimen breaks before 5% deflection. Figure 5 shows the setup used for flexural testing.

4. RESULTS AND DISCUSSION

The tensile and flexural tests were conducted as explained in the earlier section, and results are presented in Table 2. Each test was conducted 2 times, and the average value is presented in Table 2.

As presented in a table, the maximum value of tensile strength and flexural strength is different for different proportion. The composite with 5 wt% of RH and 8 wt% of RS provides maximum value for average tensile strength.

Figure 5. Flexural test setup

Table 2. Average values of tensile & flexural strength*

Expt. No.	RS (Wt%)	RH (Wt %)	Resin (Wt %)	Avg. Tensile Strength (N/mm^2)	Avg. Flexural Strength (N/mm^2)
1	5	5	90	16.25	26.995
2	5	8	87	18.095	33.335
3	5	11	84	17.015	31.12
4	5	14	81	15.07	36.04
5	5	17	78	15.675	29.1
6	8	5	87	12.295	32.97
7	8	8	84	15.57	35.52
8	8	11	81	14.34	36.825
9	8	14	78	12.28	31.76
10	8	17	75	12.91	35.695
11	11	5	84	11.835	32.7
12	11	8	81	12.13	36.655
13	11	11	78	12	34.05
14	11	14	75	10.125	24.785
15	11	17	72	14.05	23.645

*Testing at FAN Services, Advanced Materials Testing and Research Lab, Nashik

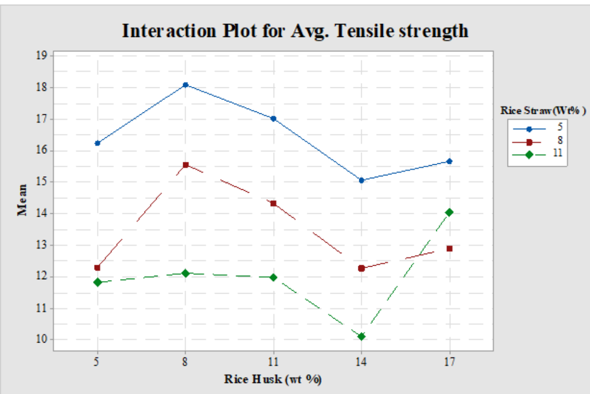

Figure 6. Interaction plot for avg. tensile strength

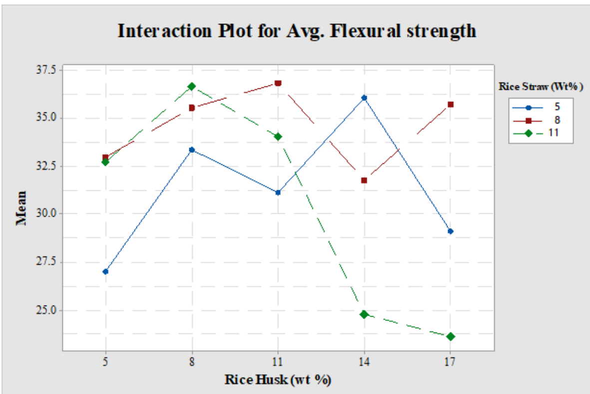

Figure 7. Interaction plot avg. flexural strength

As presented in the interaction plot for tensile strength, the rice straw and husk has a significant interactive effect on tensile strength value. At 8 wt% of RH, it provides the highest value for tensile strength for all proportions of RS. With a further increase in RH proportion, the tensile strength decreases up to 14 wt % and again further increases for 17 wt%.

On a similar line, we can observe the variation in flexural strength. At 8 wt% of RH and 11 wt% of RS, we can observe the maximum flexural strength. As presented in the interaction plot (Figure 7) for flexural strength, the rice straw and husk has a more significant interactive effect on flexural strength.

It is clear from the above analysis, that we are getting the maximum value for the tensile and flexural strength with different proportions of rice husk and straw. The specimen with a higher value of flexural strength may not provide sufficient strength in tensile conditions and vice versa.

Increasing one property may lead to compromise for another property, which is not acceptable in particular applications. In some applications, we are expecting the significant performance of NFRPC in both tensile and flexural/bending conditions. To obtain the maximum performance of specimen in both tensile and flexural testing, it is necessary to define the optimal proportion of reinforcing RH and RS to balance between tensile and flexural strength.

Grey relational analysis is a statistical technique for multi-objective optimization problems [32]. This technique helps to convert the multi-objective problem into a single objective. In this study, maximizing tensile and flexural strength are two objectives to achieve. For this objective, the optimization of RH and RS reinforcement is crucial. In this work, an attempt has been made to obtain the optimal proportion of RH and RS for maximizing tensile and flexural strength without compromising for another property. The results obtained in Table 2 were processed as per Equations 2 to 4 presented in earlier sections.

Both tensile and flexural strength were assigned an equal weightage of 50% for grey relational analysis. The results of the grey relational analysis are presented in Table 3. Weighted grey relational grade (GRG) and corresponding rank are presented in Table 3. In this table, the highest value of wt. GRG with rank 1 shows the optimal condition for RH and RS proportion for maximizing both tensile and flexural strength.

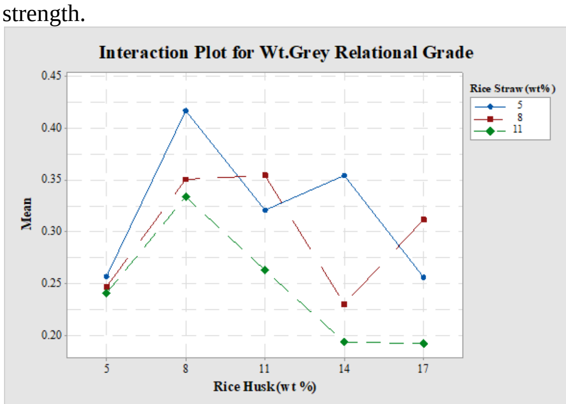

Figure 8. Interaction plot for wt. GRG

Figure 8 presents the interaction plot for a weighted grey relational grade. At 08 wt% of RH and 05 wt% of RS, we get the maximum value for weighted GRG, indicating the optimum proportion of the reinforcing materials for maximizing both properties simultaneously.

5. Analysis of variance (ANOVA)

Finally, Analysis of Variance (ANOVA) was performed to obtain the individual contribution of Wt% RS and RH for weighted Grey Relational Grade (Wt.GRG) or the individual contribution in mechanical properties. Analysis of Variance is a statistical technique that helps to identify the significance of the design/input parameter in relation to the output/desired parameter [33]. The analysis is carried out for the level of significance of 5% (the level of confidence is 95%). Table 4 shows the results of ANOVA.

It is clear from Table 4, that Wt% of RH has a significant contribution of about 51.38% in wt GRG with a P-value of 0.036 (< 0.05, significant). It is a more significant as a major factor contributing to the mechanical property improvement of NFRPC, while Wt% of RS has the contribution of about 25.20% in wt GRG or mechanical properties of NFRPC.

Table 3. Grey relational analysis

Expt. No.	RS (Wt %)	RH (Wt %)	Resin (Wt %)	Avg. Tensile Stren. (N/mm^2)	Avg. Flex. Strength (N/mm^2)	Wt. GRG	GRG Rank
1	5	5	90	16.25	26.995	0.257	9
2	5	8	87	18.095	33.335	0.417	1
3	5	11	84	17.015	31.12	0.321	6
4	5	14	81	15.07	36.04	0.355	3
5	5	17	78	15.675	29.1	0.256	10
6	8	5	87	12.295	32.97	0.247	11
7	8	8	84	15.57	35.52	0.351	4
8	8	11	81	14.34	36.825	0.355	2
9	8	14	78	12.28	31.76	0.23	13
10	8	17	75	12.91	35.695	0.312	7
11	11	5	84	11.835	32.7	0.241	11
12	11	8	81	12.13	36.655	0.334	5
13	11	11	78	12	34.05	0.263	8
14	11	14	75	10.125	24.785	0.194	14
15	11	17	72	14.05	23.645	0.192	15

Table 4. Analysis of Variance (ANOVA)

Source	DF	Seq. SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Wt% of Rice Straw	2	0.01545	25.20%	0.01545	0.007723	4.31	0.054
Wt% of Rice Husk	4	0.03149	51.38%	0.031499	0.007872	4.39	0.036 (sign.)
Error	8	0.01435	23.10%	0.001435	0.001497		
Total	14	0.06128	100%				

6. CONCLUSION

1. In the area of sustainable product development, a hybrid NFRPC of rice husk particles and rice straw has been developed and proposed with improved mechanical properties.
2. In the area of product development, it is always expected to optimize the proportion of Reinforcing 08 wt% of RH and 05 wt% of RS in polymer composite will provide us with significantly acceptable strength in both tensile and flexural loading conditions.
3. Reinforcing 08 wt% of RH and 05 wt% of RS in polymer composite will provide us with significantly acceptable strength in both tensile and flexural loading conditions.
4. From Analysis of Variance, it is clear that rice husk has significant contribution in improving mechanical properties of rice husk and straw fiber-reinforced polymer composite.

REFERENCES

[1] Jawaid M., and Abdul Khalil HPS, Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review. Carbohydrate Polymers, 2011, 86, pp.1–18.

[2] Vijaya Ramnath B., Manickavasagam VM., Elanchezhian C., Vinodh Krishna C., Karthik S., Saravanan K. Determination of mechanical properties of intra-layer abaca–jute–glass fiber reinforced composite. Materials & Design, 2014, 60: 643–652.

[3] Senthilkumar K., Saba N., Rajini N., Chandrasekar M., Jawaid M., Sienghin S. et al. Mechanical properties evaluation of sisal fibre reinforced polymer composites: a review. Construction and Building Materials, 2018, 174:713.

[4] Lila MK., Singhal A., Banwait SS., Singh I. A recyclability study of bagasse fiber reinforced polypropylene composites. Polymer Degradation and Stability, 2018, 152:272.

[5] Monteiro SN., Calado V., Rodriguez RJS., Margem FM. Thermo gravimetric stability of polymer composites reinforced with less common lignocellulosic fibers-an overview. Journal of Material Research Technology, 2012, 1(2):117.

[6] Majeed K., Hassan A., Abu Bakar A. Barrier, Biodegradation, and mechanical properties of (Rice husk)/ (Montmorillonite) hybrid filler-filled low-density polyethylene nanocomposite films. Journal of Vinyl and Additive Technology, 2017, 23:162–171.

[7] George J., Kumar R., Jayaprahash C., Ramakrishna A., Sabapathy S., Bawa A. Rice bran-filled biodegradable low-density polyethylene films: Development and characterization for packaging applications. Journal of Applied Polymer Science, 2006, 102:4514–4522.

[8] Vaisanen T., Haapala A., Lappalainen R., and Tomppo L. Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review. Waste Management, 2016, 54:62-73.

[9] Butylina S., Martikka O., Karki T. Thermal performance and optical properties of wood–polymer composites. Journal of Thermoplastic Composite Materials, 2013, 26:60–73.

[10] Jawaid M., Khalil HA. Cellulosic /synthetic fibre reinforced polymer hybrid composites: A review. Carbohydrate Polymer, 2011, 86:1–18.

[11] Layth M., Ansari M., Grace P., Mohammad J., Saiful Islam, M. A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. International Journal of Polymer Science, Vol. 2015.

[12] Kin-tak L., Pui-yan H., Min-Hao Z., David H. Properties of natural fibre composites for structural engineering applications. Composites Part B: Engineering, 2018, 136:222–233.

[13] Adam F., Appaturi JN., and Iqbal A. The utilization of rice husk silica as a catalyst: review and recent progress. Catalysis Today, 2012, 190(1):2–14.

[14] Arjmandi R., Hassan A., Majeed K., et al. Rice husk filled polymer composites. International Journal of Polymer Science, 2015: 1–32.

[15] Faruk O., Bledzki AK., Fink H., et al. Biocomposites reinforced with natural fibers: 2000–2010. Progress in Polymer Science, 2012, 37(11): 1552–1596.

[16] Ramamoorthy SK., Skrifvars M. and Persson A. A review of natural fibers used in biocomposites: plant, animal and regenerated cellulose fibers. Polymer Reviews, 2015, 55(1): 107–162.

[17] Lim SL., Wu TY., Sim EYS., et al. Biotransformation of rice husk into organic fertilizer through vermicomposting. Ecological Engineering, 2012, 41:60–64.

[18] Aprianti E., Shafigh P., Bahri S., et al. Supplementary cementitious materials origin from agricultural wastes-a review. Construction and Building Materials, 2015, 74:176–187.

[19] Mohammed L., Ansari MNM., Pua G., et al. A review on natural fiber reinforced polymer composite and its applications. International Journal of Polymer Science, 2015, 1–15.

[20] Kabir M., Wang H., Lau K., Cardona F. Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. Composites Part B: Engineering, 2012, 43: 2883–2892.

[21] Sudhakar K., and Srinivas Ch. Investigation of Mechanical Properties of Rice Straw Fibre Polypropylene Composites. International Journal of Engineering Research and Applications, 2014, 4:182-187.

[22] Gultom LA., Dirhamsyah and Dina S. Physical Properties Of Rice Straw Particle Board. Jurnal Hutan Lestari, 2013, 1:458-465.

[23] Abd El-baky MA. Evaluation of Mechanical Properties of Jute/Glass/Carbon Fibers Reinforced Hybrid Composites. Fibers and Polymers, 2017, Vol.18, No.12: 2417-2432.

[24] Pakravan HP., Jamshidi M., Asgharian Jeddi AA. Combination of ground rice husk and polyvinyl

alcohol fiber in cementitious composite. Journal of Environmental Management, 2018, 215: 116-122.

[25] Jawad K. Oleiwi, Qahtan Adnan Hamad and Hadil Jabbar Abdul Rahman. Experimental Investigation of Flexural and Impact Properties of PMMA Reinforced by Bamboo and Rice Husk Powders. International Journal of Mechanical Engineering and Techanology, 2018, 9(10):559–568.

[26] Farooq Sk, Vinay Kumar D., Optimization of Performance and Exhaust Emissions of a PFI SI Engine Operated with Iso-stoichiometric GEM Blends Using Response Surface Methodology. Jordan Journal of Mechanical and Industrial Engineering, 2021, Vol.15 (2):199-207.

[27] Shukry H., Aghdeab, Laith A., Mohammed , Alaa M. Ubaid, Optimization of CNC Turning for Aluminum Alloy Using Simulated Annealing Method. Jordan Journal of Mechanical and Industrial Engineering, 2015, Vol. 9 (1):39-44.

[28] Ghalme S., Koinkar P., Bhalerao Y. Effect of Aluminium Oxide (Al_2O_3) Nanoparticles Addition into Lubricating Oil on Tribological Performance. Tribology in Industry, 2020, Vol. 42 (3):494-502.

[29] Aslantasa K., Ekicib E., Cicek A. Optimization of process parameters for micro milling of Ti-6Al-4V alloy using Taguchi-based gray relational analysis. Measurement, 2018.

[30] Zulfiqar Ali Raza, Naseer Ahmad, Shahid Kamal. Multi-response optimization of rhamnolipid production using grey rational analysis in Taguchi method. Biotechnology Reports, 2014, 3:86–94.

[31] Prakash Kumar Sahu, Sukhomay Pal. Multi-response optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis. Journal of Magnesium and Alloys, 2015, 3:36-46.

[32] Ghalme S., Bhalerao Y., Phapale K. Analysis of Factors Affecting Delamination in Drilling GFRP Composite. Journal of Computational and Applied Research in Mechanical Engineering, 2021, Vol.10 (2): 281-289.

[33] Saadat Ali Rizvi, , Tewari S., Optimization of Welding Parameters by Using Taguchi Method and Study of Fracture Mode Characterization of SS304H Welded by GMA Welding. Jordan Journal of Mechanical and Industrial Engineering, 2018, Vol. 12 (1):17-22.