Materials Technology Reports 2024, 2(1), 1603.
https://doi.org/10.59400/mtr.v2i1.1603

Article

Performance assessment of particle board developed from organic wastes using polymer matrix

Joseph Abutu[1,*], Tsotsi Rikwen Tsoji[1], Areo Stephen[2], Aliyuda Dedan Araye[1], Sunday Albert Lawal[3], Ayuba Kitaka Rimamtaatang[1]

[1] Department of Mechanical Engineering, Taraba State University, Jalingo 660213, Nigeria
[2] National Examination Council, Minna 920101, Nigeria
[3] Department of Mechanical Engineering, Federal University of Technology, Minna 920101, Nigeria
*** Corresponding author:** Joseph Abutu, abutu.joseph@tsuniversity.edu.ng

CITATION

Abutu J, Tsoji TR, Stephen A, et al. Performance assessment of particle board from organic wastes using polymer matrix. Materials Technology Reports. 2024; 2(1): 1603.
https://doi.org/10.59400/mtr.v2i1.1603

ARTICLE INFO

Received: 14 April 2024
Accepted: 27 May 2024
Available online: 15 June 2024

Abstract: In this work, sugarcane bagasse and rice husk were used as filler material for the production of agro-based particle board along with low-density polyethylene and coconut shell, with the aim of investigating the effects of varying compositions of constituents on the performance of the developed composite using constant process parameters of moulding pressure (10 MPa), moulding temperature (140 °C), curing time (10 min) and heat treatment time (1 h). Experimental design was conducted using box-Behnken design (L1533) while multi-response optimization was carried out using grey relational analysis (GRA). The experimental results revealed that changes in percentage composition affect the performance of the composite, and the multi-response optimal performance of the developed bagasse-based particle board (BPB) and rice husk-based particle board (RPB) can be achieved with bagasse or rice husk (30 wt%), coconut shell (30 wt%), and low-density polyethylene (40 wt%). The results of the analysis of variance showed that the performance of the two particle boards is most influenced by the presence of low-density polyethylene (LDPE). Finally, compared to rice husk, bagasse can effectively serve as a preferred substitute for wood in the production of particle board.

Keywords: bagasse; rice husk; coconut shell; LDPE; GRA; particle board

1. Introduction

Particle boards are often regarded as boards produced from lingo-cellulosic materials such as wood and bonded together by resins or other adhesives [1]. These composites are often utilised in structural applications such as furniture, partitioning, ceiling boards, wall bracing, cladding, and flooring. Most of these particle boards in existence are produced from wasted wood materials, thereby conserving our natural resources [2]. Saeed et al. [3] have revealed that lignocellulosic materials, derived from agro-wastes, are vital resources comprising cellulose, lignin, and hemicellulose, which can be classified into non-wood and wood. Non-wood consists of sugarcane bagasse, coconut shells [4], rice husks [3], and pineapple leaves [5], while wood consists of softwood and hardwood [6]. Though, most recently, non-wood materials are gaining dominance as a result of global fibre demand and scarcity of trees. This is attributed to their ease of processing and short growth cycles [7]. However, with an increase in the global population and advances in technology, the demand for wood in the forest industry has grown over the years, thereby leading to an increase in deforestation, which negatively affects global climate change [8,9]. Ganaie et al. [10] have revealed that global population growth is increasing the demand for wood for

construction and increasing its price. This massive demand has resulted in the application of wood in new areas and has similarly led to a significant pressure on the existing forest resources [11,12]. Though the need to reduce the overdependence on forest resources and wood coupled with the demand for an improved particle board using agro-wastes has prompted a huge interest in the utilization of agricultural wastes and residues for the production of particle board [13]. These alternative materials can play a growing tendency and major role in providing alternatives for particle board industries. Several authors have ultilised different agro-waste materials with the aim of finding a suitable replacement for wood products and obtaining particle board with desirable properties such as high density, better mechanical properties, abrasion resistance, high durability, low water absorption, and thickness swell rate [3,14].

Auriga et al. [15] investigated the effect of the addition Tetra Pak waste material in the core layer on the performance of particle board. The authors revealed that Tetra Pak does not significantly affect the modulus of elasticity and static bending strength of the particleboard but significantly decreases tensile strength. Acda and Cabangon [16] investigated the mechanical and physical properties as well as termite resistance of particleboard developed from a mixture of wood particles and waste tobacco stalk. It was found that the presence of residual nicotine is responsible for termite resistance of particleboard containing tobacco stalk. Hence, authors revealed that tobacco stalk can be used as an alternative material for wood particles in the manufacture of particleboard. Atoyebi et al. [17] developed particle boards from coconut shell, palm kernel shell, and coconut husk in different compositions of urea formaldehyde binder varying from 25%, 30%, 35%, 40%, and 50%. The authors revealed that particle boards composed of 25% palm kernel shell, 50% coconut shell, and 25% coconut husk have the most preferable properties. Kenaf fibers have also been used by Xu et al. [18], Paridah et al. [19], and Juliana et al. [20] for the production of particle board using similar experimental design techniques (trial and error). The results provided by the different authors provided evidence that combining kenaf fiber particles with other materials leads to better mechanical and physical properties of particle boards. Also, bagasse and timber mixture from industrial waste [21], Roselle tree stem [22], Jatropha Curcas wood waste [23], hazelnut husk [24], and pepper stalks [25] are some of the agro-wastes that have been used for the production of particle boards.

Over the years, natural fibers such as bagasse have been under-utilized and their disposal has posed a major environmental concern for Africans, especially people leaving in the northern parts of Nigeria [26]. Akshaya et al. [27] have revealed that bagasse is a lingo-cellulosic material providing an abundant and renewable energy source and consists of approximately 50% cellulose and 25% each of hemicellulose and lignin. Also, Salmah [28] reported that coconut shell (lignocellulosic filler) exhibits better properties compared to mineral fillers (kaolin, mica, $CaCO_3$ and talc). Some of the outstanding properties reported by Salmah [28] include minimal health hazards, a high specific strength-to-weight ratio, low cost, biodegradability, being environmentally friendly, and renewability. In addition, rice husk (RH) is known to be an inexpensive byproduct of rice processing. Many researchers have revealed that rice husk can be utilized as filler material in rice husk-filled polymeric composites. Therefore, in this study, bagasse, coconut shells, and rice husk were used as filler materials in the production of particle board composites using low-density

polyethylene (empty water sachet) wastes as binder and adopting box Behnken design (BBD) and Julong's grey relational analysis (GRA) as experimental design and multi-response optimization technique, respectively.

2. Materials and methods

2.1. Materials

Bagasse (**Figure 1a**), coconut shells (**Figure 1b),** and rice husk (**Figure 1c**) were utilized separately as filler materials, while low-density polyethylene (empty water sachet) wastes (**Figure 2**) were used as binder. Bagasse was locally sourced from Savanna Sugar Company, Numan, Nigeria; coconut shells were sourced from a coconut trader in Jalingo, Nigeria; and rice husk was obtained from a local rice milling factory in Jalingo, Nigeria. Also, the empty water sachet wastes were picked from the main campus of Taraba State University, Jalingo, Taraba State.

(a) **(b)** **(c)**

Figure 1. Filler materials: **(a)** sugarcane bagasses; **(b)** coconut shells; **(c)** rice husk.

Figure 2. Low density polyethylene (sachet water) wastes.

2.2. Methods

This research was carried out in three stages; the first stage involved the preparation of the locally sourced bagasse, coconut shells, and rice husk using distilled water and sodium hydroxide. The second stage involved the production and characterization of particle boards developed separately from bagasse and rice husk using low-density polyethylene binder and coconut shells via box Behnken design (BBD), and the final stage involved the analysis of the experimental data using a single response (signal to noise ratios) and multi-response (grey relational analysis) optimization technique.

2.2.1. Material preparation

The locally sourced rice husk and bagasses were immersed in sodium chloride (NaCl) solution for treatment and thereafter dried under the sun for 5 days to remove the moisture content. The dried sugarcane bagasses were then crushed using a blender to produce short, needle-like fibers. Also, the preparation of the coconut shells involved washing of shells with soap (sodium sulfonate) and cleaning using dried cloth, drying in a hot air oven (150 °C), followed by crushing using a pestle and mortar as well as grinding with a grinding machine. The blended bagasse, coconut shell powder, and rice husks were then sieved using a sieve size 425 µm. In addition, the empty water sachet wastes made of low-density polyethylene (LDPE) were also picked, sorted, and washed thoroughly to remove debris and dirt that may stand as impurities. The sachet water wastes were then dried under the sun for 5 days to remove retained moisture on the sachet. Thereafter, the dried sachets were cut into smaller pieces for easy compounding and then measured accordingly. The methods of preparation of the different materials are presented in **Figure 3**.

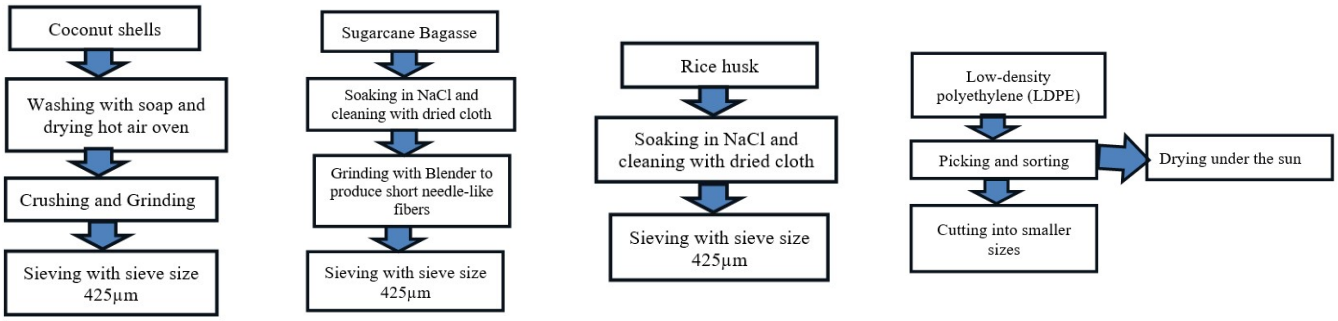


Figure 3. Methods of preparation of **(a)** coconut shells; **(b)** sugarcane bagasse; **(c)** rice husk; **(d)** LDPE.

2.2.2. Experimental design

Experimental design was carried out in accordance with box Behnken-response surface methodology $L_{15}(3)^3$ design using Minitab 19 statistical software. A varying composition (control factors) of reinforcement (bagasse or rice husk), LDPE, and a constant coconut shell powder was used to investigate the effects of composition on the performance of the developed composite. Constant process parameters of moulding pressure (10 MPa), moulding temperature (140 °C), curing time (10 min), and heat treatment time (1 h) were also used in this study. The factor levels of the control factors utilised in the work are shown in **Table 1**, while the box Behnken's design (BBD) matrix consisting of the coded and experimental matrix was obtained using Minitab 19 statistical software and shown in **Table 2**. The factor levels presented in **Table 1** are selected based on the volume size of the mould and recommendations by other authors stipulated in literature [17,29]. Also, Lekshmi et al. [30] recommended equal composition for binder (low density polyethylene) and reinforcement (rice husk and bagasse). Hence, similar factor levels (150 = 350 g) were adopted for the two control factors in this study. In addition, the mass of the coconut shells was held constant throughout. The total weight utilized was 150 g, as adopted by Suleiman et al. [31].

Table 1. factor levels of control factors.

Control factors	Unit	Level 1	Level 2	Level 3
Low density polyethylene	Gram	150	250	350
Reinforcement (*R*)	Gram	150	250	350
Coconut shell (CCS)	Gram	150	150	150

Table 2. Coded and experimental design matrix.

Sample number	Coded matrix			Experimental matrix (grams)			Experimental matrix (%)		
	R	**CCS**	**LDPE**	**Ba/Rh**	**CCS**	**LPD**	***R***	**CCS**	**LDPE**
1	−1	−1	0	150	150	150	33.3	33.3	33.3
2	1	−1	0	350	150	150	53.8	23.1	23.1
3	−1	1	0	150	150	150	33.3	33.3	33.3
4	1	1	0	350	150	150	53.8	23.1	23.1
5	−1	0	−1	150	150	100	37.5	37.5	25.0
6	1	0	−1	350	150	100	58.3	25.0	16.7
7	−1	0	1	150	150	200	30.0	30.0	40.0
8	1	0	1	350	150	200	50.0	21.4	28.6
9	0	−1	−1	250	150	100	50.0	30.0	20.0
10	0	1	−1	250	150	100	50.0	30.0	20.0
11	0	−1	1	250	150	200	41.7	25.0	33.3
12	0	1	1	250	150	200	41.7	25.0	33.3
13	0	0	0	250	150	150	45.5	27.3	27.3
14	0	0	0	250	150	150	45.5	27.3	27.3
15	0	0	0	250	150	150	45.5	27.3	27.3

2.2.3. Production processes

Two sets of particle boards were produced using bagasse and rice husk separately as reinforcement materials, and coconut shell was used as filler particles. The sieved bagasse, or rice husk, coconut shell, as well as the LDPE, was measured as specified for each composition presented in **Table 2**. For each run, a two-roll mill situated at the polymer workshop of the Nigerian Institute for Leather and Science Technology (NILEST), Samaru, Zaria-Nigeria, was used to blend the mixture in order to form the composite. The compounded mixture was thereafter removed and placed in a square mould of dimensions 150 × 100 × 30 mm for hot pressing in order to increase its compatibility. The hot-pressing process was carried out using a compression moulding machine (Model: 0577-86365889, Wenzhou Zhiguang Shoe Machine Co. Ltd.) situated at the polymer workshop of the Nigerian Institute for Leather and Science Technology (NILEST), Samaru, Zaria, Nigeria. and constant coconut shell powder and process parameters (moulding pressure—10 MPa, moulding temperature—140 °C, and curing time—10 min) were used throughout the compression moulding process. At the end of the compression moulding cycle, the boards were removed and subjected to heat treatment for 1 h using a hot air oven operating at a temperature of 120 °C. The same procedure was used for the production of the other fourteen (14) samples. The developed bagasse and rice husk-based reinforced particle boards are

presented in **Figures 4** and **5**, respectively. Samples 1–4 and samples 13–15 shown in **Figures 4** and **5** contain 150 g of LDPE, while samples 10–15 constitute 250 g of sugarcane bagasse (**Figure 4**) and rice husk (**Figure 5**). Other samples shown in **Figures 4** and **5** contain 150 g of coconut shall and were produced in accordance with the experimental design matrix presented in **Table 2**.

Figure 4. Bagasse-based reinforced particle board.

Figure 5. Rice husk-based reinforced particle board.

2.2.4. Sample characterization

The developed particle board samples were characterized by investigating the performance (tensile strength, impact energy, hardness, thickness swell, and water absorption). The tensile strength, impact energy, and hardness of the board were studied using standard testing procedures specified by ASTM D638, ASTM E23-04, and ASTM E384, respectively, while thickness swell and water absorption were studied using standard testing procedures specified by ASTM D570. Hardness test samples were prepared to 40 × 40 × 20 mm dimension, and the test was carried out using a Vicker's hardness tester (Model: MV1-PC, Serial No: 07/2012-1329) with a load of 0.3 kg by setting the machine to a maximum and minimum limit of 120 and 020 HV. As recommended by ASTM E384, hardness tests were conducted using a loading force of 0.3 kg, and the hardness was determined by the penetration depth of the indenter under the applied load. At least three readings of each measured point

were taken. Also, specimens for the tensile test were prepared in accordance with standard ASTM D638 (ASTM International 2004-Dumbell shape) for each sample using a universal testing machine (INSTRON; 6800 series, Max: 50 kN) and executed at room temperature. Three specimens from each sample were prepared in accordance with the specified ASTM standards, and the average value of the results was thereafter recorded. In addition, the specimen for the impact test was prepared to 20 × 20 × 10 mm in accordance with ASTM E23-04 guidelines. This procedure involved placing the V-notched specimen across the parallel jaws of the impact testing machine in the Charpy mode, after which the pointer was set to an initial energy of 0 J and thereafter, releasing the pendulum hammer downward towards the specimen. The energy absorbed, which causes the fractured surfaces, was then recorded. Three test specimens prepared from each sample were tested and the average values recorded. Also, specimens for the water absorption and thickness swell test were prepared in accordance with the procedure outlined by ASTM D570, which stipulates a specimen size of 20 × 20 × 3 mm prepared from each sample. Ten specimens of each sample were prepared and dried in an oven for 24 h at 50 ℃. The samples were thereafter removed and allowed to cool. Specimens for thickness swell and water absorption tests were afterward immersed in distilled water for 3 days. The water absorption and thickness swell of each sample will be calculated using Equations (1) and (2), respectively [32].

$$\text{Water absorption (Wa)} = \frac{W_1 - W_0}{W_0} \times 100 \quad (1)$$

$$\text{Thickness swell (Ts)} = \frac{T_1 - T_0}{T_0} \times 100 \quad (2)$$

W_1 and W_0 = weight of specimen after and before immersion in distilled water; T_1 and T_0 = Thickness of specimen after and before immersion in distilled water; Theoretically, ultimate tensile strength and impact strength can be calculated using Equations (3) and (4) respectively [33].

$$\text{Ultimate tensile strength (UTS)} = \frac{P_{\max}}{A_0} \quad (3)$$

where P_{max} = maximum load, A_0 = original cross sectional area.

$$\text{Impact strength (Ie)} = \frac{\text{Impactenergy}}{A} \quad (4)$$

where; A = area under the notch.

2.2.5. Analysis of experimental results

In order to achieve optimization and investigate the percentage contribution of individual control factors on the performance of the developed particle board, experimental results obtained from performance examination (tensile, impact energy, hardness, thickness swell, and water absorption) were analyzed using the signal-to-noise (SN) ratio and analysis of variance (ANOVA), respectively. SN ratio values for tensile strength, impact energy, and hardness were calculated using larger-the-better quality characteristics (Equation (5)), while those of thickness swell and water absorption were calculated using smaller-the-better quality characteristics (Equation (6)). All analysis was carried out using a confidence level of 95% and a significance level of 5%.

Larger-the better:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i-1}^{n}\frac{1}{y_i^2}\right) \quad (5)$$

Smaller-the better:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i-1}^{n}y_i^2\right) \quad (6)$$

where, n = number of experimental samples and y = responses of given factor level combination.

2.2.6. Microstructural examination

Fractured surfaces of the optimised tensile test specimen produced using optimal values of composition obtained from GRA were observed using a scanning electron microscope (JEOL, Model No: JSM-7600F, USA) operating at an accelerating voltage of 10 kV after gold sputter coating. Images of the fractured sample were obtained using a magnification of 100× by scanning the test specimens with a focused beam of electrons, which provides information about the surface topography and composition of the sample.

2.2.7. Proposed methods with recently published related works

The methods adopted in this study compared with recently published work are presented in **Table 3**. It can be observed that the experimental technique used in most studies is trial-and-error. However, this study adopted Box-Behnken's design technique. Thereby, reducing the number of experiments, ensuring appropriate data collection and analysis, and also ensuring that conclusions from this study are valid. Also, compared to other recent studies, agro-wastes were utilized along with waste sachet LDPE. Hence, reducing the cost of production and nuisance posed by these wastes to the environment.

Table 3. Proposed methods with recently published related works.

Parameters	Present work	Yang et al. [34]	Chandran et al. [35]	Krumins et al. [36]
Reinforcement materials	Rice husk and Bagasse (used separately)	ACQ-treated wood and rainscreen bar-treated wood	Rice husk and coconut fiber	Conifer bark
Binder used	LDPE (waste water sachet)	urea–melamine formaldehyde resin	unsaturated polyester resin	Bio-adhesives
Experimental Design technique	Box-Behnken's Design Technique	Trial and error method	Trial and error method	Trial and error method
Number of samples produced	Fifteen	Five	three	Three
Properties investigated	Tensile strength, impact energy, hardness, water absorption, thickness swell and microstructure	Density and moisture content, thickness swelling, water absorption, bending strength and Internal bond strength	Water absorption, thickness swelling, modulus of elasticity and modulus of rupture.	Density, bending strength and modulus of rupture
Production parameters used	Moulding pressure—10 MPa, moulding temperature—140 °C and curing time—10 min	Moulding temperature (200 °C), moulding pressure (100 kgf/cm^3) and curing time (15 min)	Moulding temperature (65 °C) and curing time (2 h)	Moulding temperature (40–160 °C), moulding pressure (1–5 MPa)

3. Results and discussion

3.1. Experimental results

The summary of the experimental results for properties of the developed particle boards along with their corresponding signal-to-noise (SN) ratio values for bagasse-based particle board (BPB) and rice husk-based particle board (RPB) are shown in **Tables 3** and **4**, respectively. The results for BPB in **Table 3** showed ultimate tensile strength (UTS), impact energy (Ie), hardness (Ha), water absorption (Wa), and thickness swell (Ts) fall within 9.19 ± 6.08 MPa, 1.771 ± 1.097 J/mm^2, 68 ± 47 HV, 1.924% ± 1.191%, and 1.577 ± 0.977, respectively, while the results for RPB presented in **Table 4** revealed that ultimate tensile strength (UTS), impact energy (Ie), hardness (Ha), water absorption (Wa), and thickness swell (Ts) fall within 7.33 ± 4.54 MPa, 1.322 ± 0.819 J/mm^2, 61 ± 42 HV, 5.011% ± 2.723%, and 3.929 ± 2.053, respectively. The bagasse-based particle board (BPB) showed better performance compared to the rice husk-based particle board (RPB). This may be attributed to the higher dendrite size and formation of coarse grain structure in the composite [37]. In addition, the SN ratio measures how the response varies relative to the target value under different noise conditions. Anugraha et al. [38] have revealed higher values of the SN ratios identify control factor settings that minimize the effects of the noise factors. Hence, the values in **Tables 4** and **5** indicate the signal levels (response value) for tensile strength, hardness, and impact energy are greater than the experimental noise level, while those of water absorption and thickness swell showed more influence of experimental noise, which slightly tends to affect the response or signal values. However, samples with higher SN values showed better signal quality (response value).

Table 4. Experimental results and SN ratio values for BPB.

Run	Experimental results					Signal-to noise ratios (dB)				
	UTS (Mpa)	Ie (J/mm^2)	Ha (HV)	Ts (%)	Wa (%)	UTS	Ie	Ha	Ts	Wa
1	9.19	1.659	65	1.265	1.037	19.266	4.397	36.253	−2.042	−0.316
2	6.73	1.479	53	1.606	1.317	16.560	3.399	34.426	−4.115	−2.392
3	7.28	1.477	47	1.603	1.315	17.243	3.388	33.449	−4.099	−2.379
4	6.19	1.675	48	1.819	1.491	15.834	4.480	33.654	−5.197	−3.470
5	9.02	1.116	59	1.477	1.212	19.104	0.953	35.470	−3.388	−1.670
6	6.46	1.166	62	1.800	1.476	16.205	1.334	35.792	−5.105	−3.382
7	9.82	1.627	68	1.191	0.977	19.842	4.228	36.691	−1.518	0.202
8	9.29	1.361	55	1.212	0.994	19.360	2.677	34.788	−1.670	0.052
9	6.59	1.097	52	1.766	1.448	16.378	0.804	34.240	−4.940	−3.215
10	6.08	1.214	48	1.924	1.577	15.678	1.684	33.654	−5.684	−3.957
11	8.20	1.400	64	1.425	1.168	18.276	2.923	36.102	−3.076	−1.349
12	8.19	1.771	59	1.317	1.080	18.266	4.964	35.470	−2.392	−0.668
13	7.54	1.383	60	1.501	1.231	17.547	2.816	35.632	−3.528	−1.805
14	7.60	1.324	59	1.483	1.215	17.616	2.438	35.470	−3.423	−1.692
15	7.66	1.371	58	1.488	1.220	17.685	2.741	35.304	−3.452	−1.727

Table 5. Experimental results and SN ratio values for RPB.

Run	Experimental results					Signal-to noise ratios (dB)				
	UTS (Mpa)	Ie (J/mm^2)	Ha (HV)	Wa (%)	Ts (%)	UTS	Ie	Ha	Wa	Ts
1	6.86	1.238	58	2.952	2.241	16.726	1.854	35.269	−9.402	−7.009
2	5.02	1.104	47	4.018	3.115	14.014	0.859	33.442	−12.080	−9.869
3	5.43	1.102	42	4.01	3.108	14.696	0.844	32.465	−12.063	−9.850
4	4.62	1.25	43	4.683	3.66	13.293	1.938	32.669	−13.410	−11.270
5	6.73	0.833	53	3.617	2.786	16.560	−1.587	34.486	−11.167	−8.900
6	4.82	0.87	55	4.625	3.613	13.661	−1.210	34.807	−13.302	−11.157
7	7.33	1.214	61	2.723	2.053	17.302	1.684	35.707	−8.701	−6.248
8	6.93	1.016	49	2.788	2.106	16.815	0.138	33.804	−8.906	−6.469
9	4.92	0.819	46	4.519	3.525	13.839	−1.734	33.255	−13.101	−10.943
10	4.54	0.906	43	5.011	3.929	13.141	−0.857	32.669	−13.998	−11.886
11	6.12	1.045	57	3.453	2.651	15.735	0.382	35.117	−10.764	−8.468
12	6.11	1.322	53	3.116	2.375	15.721	2.425	34.486	−9.872	−7.513
13	5.63	1.032	54	3.69	2.846	15.010	0.274	34.648	−11.341	−9.085
14	5.67	0.988	53	3.634	2.798	15.072	−0.105	34.486	−11.208	−8.937
15	5.72	1.023	52	3.649	2.813	15.148	0.198	34.320	−11.243	−8.983

3.2. Analysis of variance

The results of the analysis of variance (ANOVA) conducted using a confidence level of 95% and significant levels of 5% are shown in **Tables 6–9**. The notations DOF, SS, MS, *F*, and *P* were used to represent degree of freedom, sum of squares, *f*-value, and percentage contributions, respectively. Coconut shell was not included in this analysis because all factor levels have the same values; hence, the impact of the materials on the performance of the developed particle board at all levels is considered insignificant. Based on the results obtained, it can be found that the performance of the developed particle board is most influenced by the presence of low density polyethylene (LDPE), with a percentage contribution of 49.7% (UTS), 77.7% (impact energy), 51.3% (hardness), 69.6% (thickness swell), and 69.61% (water absorption) for BPB and a percentage contribution of 50.23% (UTS), 76.1% (impact energy), 51.4% (hardness), 68.5% (thickness swell), and 69.8% (water absorption) for RPB. The effects of all the factors on the performance of the developed particle boards are significant since their *p*-values are greater than 0.010 (1%). However, a percentage error of less than 5% obtained indicates experiments were performed with minimal noise effects [39].

Table 6. ANOVA for mechanical properties of BPB.

Factor	DOF	UTS				Impact energy				Hardness			
		SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)
Bagasse	2	9.21	4.60	45.94	45.4	0.13	0.064	78.66	20.9	262.8	131.4	46.2	43.9
LDPE	2	10.09	5.04	50.34	49.7	0.48	0.238	292.2	77.7	307.0	153.5	54.0	51.3
Error	8	1.00	0.10		4.94	0.01	0.001		1.3	28.5	2.8		4.8
Total	14	20.30	1.45		100	0.61	0.044		100.0	598.3	42.7		100

Table 7. ANOVA for physical properties of BPB.

Factor	DOF	Thickness swell				Water absorption			
		SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)
Bagasse	2	0.21	0.10	64.6	28.2	0.14	0.07	59.60	28.04
LDPE	2	0.51	0.25	159.5	69.6	0.34	0.17	148.00	69.61
Error	8	0.02	0.00		2.2	0.01	0.00		2.35
Total	14	0.73	0.05		100.0	0.49	0.03		100.00

Table 8. ANOVA for mechanical properties of RPB.

Factor	DOF	UTS				Impact energy				Hardness			
		SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)
Rice husk	2	5.19	2.60	59.93	45.94	0.07	0.033	20.60	19.3	210.1	105.0	48.8	44.0
LDPE	2	5.67	2.84	65.52	50.23	0.26	0.130	81.39	76.1	245.3	122.7	57.0	51.4
Error	8	0.43	0.04		3.83	0.02	0.002		4.7	21.5	2.2		4.50
Total	14	11.30	0.81		100.00	0.34	0.024		100.0	476.9	34.1		100.0

Table 9. ANOVA for physical properties of RPB.

Factor	DOF	Thickness swell				Water absorption			
		SS	MS	*F*	*P* (%)	SS	MS	*F*	*P* (%)
Rice husk	2	1.9	0.96	30.9	27.1	1.36	0.68	79.44	28.4
LDPE	2	4.9	2.44	78.3	68.5	3.34	1.67	195.60	69.8
Error	8	0.3	0.03		4.4	0.09	0.01		1.80
Total	14	7.1	0.51		100.0	4.78	0.34		100.0

3.3. Grey relational analysis

Multi-response optimization of experimental data was carried out using grey relational analysis (GRA). As suggested by Abutu et al. [29], the GRA procedure involved utilizing SN ratio values presented in **Tables 3** and **4** to calculate the grey relational generation (GRG) using larger-the-better attributes shown in Equation (7) for mechanical properties (UTS, impact energy, and hardness) and smaller-the-better attributes shown in Equation (8) for physical properties (thickness swell and water absorption). The calculation of GRG was followed by grey relation coefficient (GRC) calculation using Equation (9) and thereafter, grey relational grade (GR-grade) using Equation (10). The final process of GRA is the determination of optimal conditions for the single response.

$$\text{Larger} - \text{thebetterattributes}\ (y_{ij}) = \frac{p_{ij} - \underline{p_i}}{\overline{p_i} - p_j} \tag{7}$$

$$\text{Smaller} - \text{thebetterattributes}\ (x_{ij}) = \frac{\overline{p_j} - p_{ij}}{\overline{p_j} - \underline{p_j}} \tag{8}$$

(i = 1, 2, 3, 4, …, u and j = 1, 2, 3, 4, …, v).

where, $p_i = p_{i1}, p_{i2}, ..., p_{ij}, \ldots, p_{in}$), p_{ij} = the performance value of attribute j of alternative i and $\overline{p_i} = \max\{p_{ij}, i = 1, 2, ..., u\}$ and $\underline{p_i} = \min\{p_{ij}, i = 1, 2, ..., v\}$.

$$GRC(GRC_{oj}, GRC_{ij}) = \frac{\tau_{\min} + E\tau_{\max}}{\tau_{ij} + E\tau_{\max}} \quad (9)$$

where, E is the distinguishing coefficient. Kuo et al. [40] and Abutu et al. [29] reported that 0.5 is the widely accepted value of E.

$\tau_{ij} = p_{oj} - p_{ij}$, $\tau\Delta_{\min} = \min(\tau_{ij}, i = 1, 2, ..., u; j = 1, 2, ..., v)$ and $\tau_{\max} = \max(\Delta_{ij}, i = 1, 2, ..., u; j = 1, 2, ..., v)$.

$$\text{GR} - \text{grade} = \frac{\text{Individual GRC}}{\text{Number of experimental responses}} \quad (10)$$

Tables 10 and **11** show the values of the calculated grey relational generation, grey relational coefficient (GRC), and grey relational grade (GRG) for BPB and RPB, respectively, while the resulting factor effects of the process parameters for BPB and RPB are presented in **Tables 12** and **13**, respectively. The values in bold indicate the optimal level for each process parameter. The main effect plots obtained using the values in **Tables 11** and **12** are shown in **Figures 6** and **7**, respectively.

Table 10. GRG, GRC and GR-grades for BPB.

	GRG					**GRC**					**GR-grade**
Sn	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	
X_o	1.000	1.000	1.000	1.000	1.000						
1	0.862	0.864	0.865	0.126	0.088	0.783	0.786	0.787	0.364	0.354	0.615
2	0.212	0.624	0.301	0.623	0.441	0.388	0.571	0.417	0.570	0.472	0.484
3	0.376	0.621	0.000	0.620	0.438	0.445	0.569	0.333	0.568	0.471	0.477
4	0.037	0.884	0.063	0.883	0.624	0.342	0.811	0.348	0.811	0.571	0.576
5	0.823	0.036	0.623	0.449	0.318	0.738	0.341	0.570	0.476	0.423	0.510
6	0.127	0.127	0.723	0.861	0.609	0.364	0.364	0.643	0.782	0.561	0.543
7	1.000	0.823	1.000	0.000	0.000	1.000	0.739	1.000	0.333	0.333	0.681
8	0.884	0.450	0.413	0.036	0.025	0.812	0.476	0.460	0.342	0.339	0.486
9	0.168	0.000	0.244	0.821	0.581	0.375	0.333	0.398	0.737	0.544	0.477
10	0.000	0.212	0.063	1.000	0.707	0.333	0.388	0.348	1.000	0.630	0.540
11	0.624	0.509	0.818	0.374	0.264	0.571	0.505	0.733	0.444	0.404	0.531
12	0.622	1.000	0.623	0.210	0.148	0.569	1.000	0.570	0.388	0.370	0.579
13	0.449	0.484	0.673	0.482	0.341	0.476	0.492	0.605	0.491	0.431	0.499
14	0.465	0.393	0.623	0.457	0.322	0.483	0.452	0.570	0.480	0.424	0.482
15	0.482	0.466	0.572	0.464	0.328	0.491	0.483	0.539	0.483	0.427	0.485

Table 11. GRG, GRC and GR-grades for RPB.

	GRG					**GRC**					**GR-grade**
Sn	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	
X_o	1.000	1.000	1.000	1.000	1.000						
1	0.862	0.863	0.865	0.132	0.135	0.783	0.785	0.787	0.366	0.366	0.617
2	0.210	0.623	0.301	0.638	0.642	0.388	0.570	0.417	0.580	0.583	0.508
3	0.374	0.620	0.000	0.635	0.639	0.444	0.568	0.333	0.578	0.581	0.501
4	0.037	0.883	0.063	0.889	0.891	0.342	0.810	0.348	0.818	0.821	0.628
5	0.822	0.035	0.623	0.466	0.470	0.737	0.341	0.570	0.483	0.486	0.524

Table 11. (*Continued*).

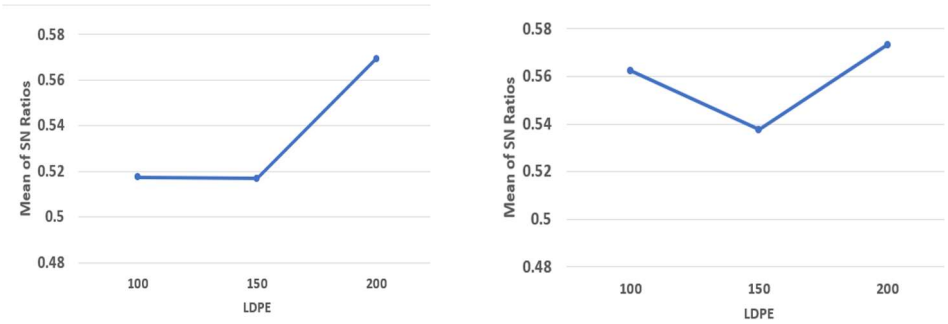
	GRG					GRC					GR-grade
Sn	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	**UTS**	**Ie**	**Ha**	**Ts**	**Wa**	
6	0.125	0.126	0.722	0.869	0.871	0.364	0.364	0.643	0.792	0.795	0.591
7	1.000	0.822	1.000	0.000	0.000	1.000	0.737	1.000	0.333	0.333	0.681
8	0.883	0.450	0.413	0.039	0.039	0.810	0.476	0.460	0.342	0.342	0.486
9	0.168	0.000	0.244	0.831	0.833	0.375	0.333	0.398	0.747	0.749	0.521
10	0.000	0.211	0.063	1.000	1.000	0.333	0.388	0.348	1.000	1.000	0.614
11	0.623	0.509	0.818	0.389	0.394	0.570	0.504	0.733	0.450	0.452	0.542
12	0.620	1.000	0.623	0.221	0.224	0.568	1.000	0.570	0.391	0.392	0.584
13	0.449	0.483	0.673	0.498	0.503	0.476	0.492	0.605	0.499	0.502	0.515
14	0.464	0.392	0.623	0.473	0.477	0.483	0.451	0.570	0.487	0.489	0.496
15	0.482	0.465	0.572	0.480	0.485	0.491	0.483	0.539	0.490	0.493	0.499

Table 12. Resulting factor effects of process parameters (BPB).

Factor	Level 1 (−1)	Level 2 (0)	Level 3 (+1)
Bagasse	**0.5708**	0.5133	0.5223
LDPE	0.5175	0.5169	**0.5693**

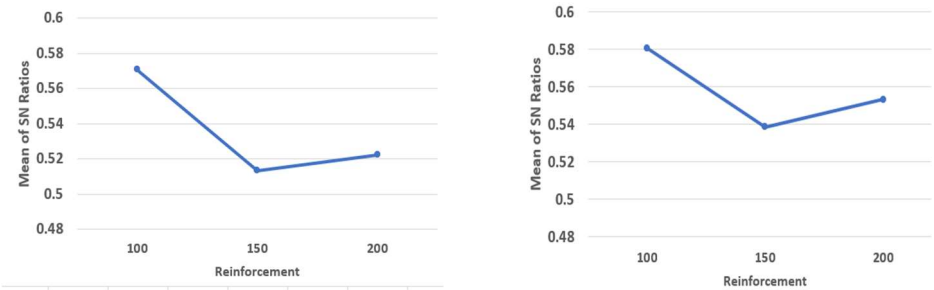
Table 13. Resulting factor effects of process parameters (RPB).

Factor	Level 1 (−1)	Level 2 (0)	Level 3 (+1)
Rice husk	**0.5808**	0.5387	0.5533
LDPE	0.5625	0.5377	**0.5733**



(a) **(b)**

Figure 6. Plots of factor effects for LDPE **(a)** BPB; **(b)** RPB.



(a) **(b)**

Figure 7. Plots of factor effects for reinforcement **(a)** BPB; **(b)** RPB.

From **Figures 6** and **7**, it can be observed that the multi-response optimum performance of both bagasse and rice husk-based particle board can be obtained using 150 g, 150 g, and 200 g of coconut shells, rice husk or bagasse, and low-density polyethylene (LDPE), respectively. This result is in agreement with the work of Baharuddin et al. [41], who revealed that the quantity of polymer-based binder used in particle board production plays an important role in the quality of the composite. This was also reflected in the results obtained from the analysis of variance presented in **Tables 5–8**.

3.4. Empirical model equations

Empirical model equations for BPB and RPB are presented in Equations (11)–(20). *A*, *B*, and *C* have been used as notations for bagasse, low-density polyethylene, and rice husk, respectively. These equations were obtained with the aid of Minitab 19 statistical software by utilizing a confidence level of 95% and significant levels of 5%. As shown in Equations (11)–(20), it can be observed that the values of some of the regression coefficients (Rsq_{adj}) presented in **Table 14** fall below 80%. This may be attributed to a noise effect resulting from experimental uncertainty [39]. However, the values obtained were in close agreement with the recommended value (80%). Hence, these model equations can be utilised for prediction of the developed particle board properties.

For BPB:

$$\text{UTS (MPa)} = 19.05 - 0.0549A - 0.0724B + 0.000063A \times A + 0.000218B \times B + 0.000102A \times B \quad (11)$$

Rsq = 77.32% and $Rsq_{(adj)}$ = 64.73%.

$$\text{Ie (J/mm}^2\text{)} = -0.429 - 0.00137A + 0.02372B + 0.000007A \times A - 0.000053B \times B - 0.000016A \times B \quad (12)$$

Rsq = 69.25% and $Rsq_{(adj)}$ = 52.17%.

$$\text{Ha (HV)} = 46.8 + 0.089A - 0.045B + 0.000002A \times A + 0.00102B \times B - 0.000784A \times B \quad (13)$$

Rsq = 78.65% and $Rsq_{(adj)}$ = 59.20%.

$$\text{Wa (\%)} = 0.629 + 0.00534A + 0.00211B - 0.000005A \times A - 0.000009B \times B - 0.000012A \times B \quad (14)$$

Rsq = 76.34% and $Rsq_{(adj)}$ = 63.20%.

$$\text{Ts (\%)} = 0.760 + 0.00655A + 0.00262B - 0.000006A \times A - 0.000011B \times B - 0.000015A \times B \quad (15)$$

Rsq = 76.35% and $Rsq_{(adj)}$ = 63.22%.

For RPB:

$$\text{UTS (Mpa)} = 14.20 - 0.0409C - 0.0540B + 0.000047C \times C + 0.000163B \times B + 0.000076C \times B \quad (16)$$

Rsq = 77.26% and $Rsq_{(adj)}$ = 64.62%.

$$\text{Ie (J/mm}^2\text{)} = -0.318 - 0.00102C + 0.01767B + 0.000005C \times C - 0.000039B \times B - 0.000012C \times B \quad (17)$$

Rsq = 69.21% and $Rsq_{(adj)}$ = 52.11%.

$$\text{Ha (HV)} = 41.8 + 0.079C - 0.040B + 0.000002C \times C + 0.00091B \times B - 0.000700C \times B \quad (18)$$

Rsq = 88.65% and $Rsq_{(adj)}$ = 69.20%.

$$\text{Wa (\%)} = 0.96 + 0.0167C + 0.0066B - 0.000016C \times C - 0.000029B \times B - 0.000039C \times B \quad (19)$$

Rsq = 76.36% and $Rsq_{(adj)}$ = 63.22%.

$$\text{Ts (\%)} = 1.39 + 0.0204C + 0.0081B - 0.000020C \times C - 0.000035B \times B - 0.000047C \times B \quad (20)$$

Rsq = 76.34% and $Rsq_{(adj)}$ = 63.20%.

Table 14. Correlation coefficient (Rsq) for developed particle boards.

Response	BPB		RPB	
	Rsq (%)	**$Rsq_{(adj)}$ (%)**	**Rsq (%)**	**$Rsq_{(adj)}$ (%)**
Ultimate tensile strength (MPa)	77.32	64.73	77.26	64.62
Impact energy (J/mm^2)	69.25	52.17	69.21	52.11
Hardness (HV)	78.65	59.20	88.65	69.20
Water absorption (%)	76.34	63.20	76.36	63.22
Thickness swell (%)	76.35	63.22	76.34	63.20

3.5. Microstructure examination

The microstructures of the optimized samples of BPB and RPB obtained are presented in **Figures 8** and **9**, respectively. **Figure 8** shows basically ductile behaviour and revealed uniform distribution of bagasse fibers and coconut shell particles with patches of the LDPE in the developed particle board. Overall observation indicates that the particles of the BPB samples showed very good dispersion of the bagasse and coconut shells. Generally, there was better dispersion between the bagasse fiber, coconut shells, and LDPE matrix with little or no presence of voids in the sample. Unlike BPB, the SEM image of RBP shown in **Figure 9** revealed basically brittle behaviour with uniform distribution of rice husk and coconut shell particles having patches of the LDPE in the sample. Overall observation also indicates that the particles of the RPB samples showed good dispersion of rice husk and coconut shells, though the internal agglomeration observed in the sample may be attributed to non-homogenous particle distribution resulting from a large number of irregularities and structures that tend to collapse under pressure and heat during pressing [42]. De Barros Filho et al. [43] have argued that the amount of collapsed thin-walled particles is dependent on the level of damage caused by hot pressing, which may lead to more intimate contacts between the matrix, rice husk, and coconut shell particles. However, these collapsed thin-walled particles can result in a reduction of mechanical properties such as a reduction in modulus of rupture, tensile strength, hardness, and impact strength [44]. Suherman et al. [45] also reported that the amount of voids in a composite is dependent on the filler/resin content and processing conditions, which in turn affect its performance.

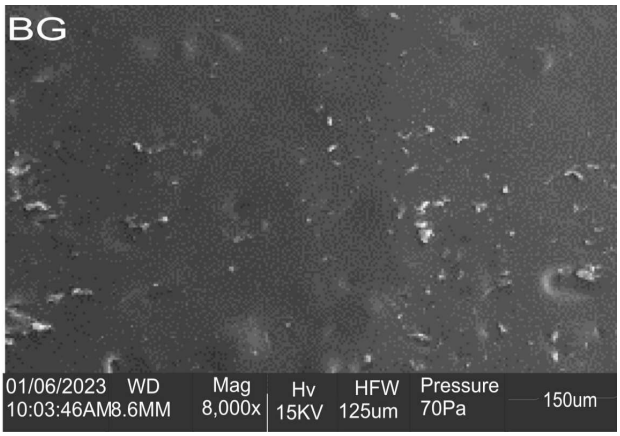


Figure 8. Microstructure of optimized BPB sample.

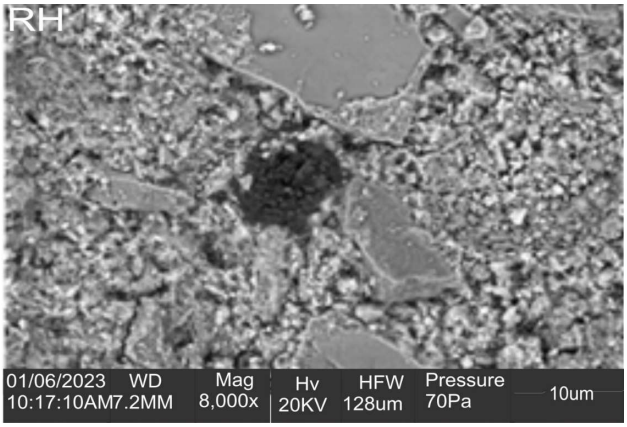


Figure 9. Microstructure of optimized RPB sample.

4. Conclusions

In this study, agro-waste (bagasse, coconut shells, and rice husk) was used as filler materials for the production of particle board. The study also utilized Box-Behnken's design to investigate the effects of composition on the performance of the developed particle board. Based on the result obtained, the following conclusions can be made:

1) Changes in percentage composition affect the performance of the composite, as all the developed particle boards possess varying performance.
2) The performance of the developed bagasse-based particle board (BPB) and rice husk-based particle board (RPB) is most influenced by the presence of low-density polyethylene (LDPE).
3) The multi-response optimum performance of BPB and RPB can be obtained using bagasse or rice husk (30 wt%), coconut shell (30 wt%), and low-density polyethylene (40 wt%).
4) There was better dispersion between the constituents of BPB, which revealed ductile behaviour with little or no presence of voids in the sample. While the microstructure of RPB revealed brittle behaviour with uniform distribution of constituent materials along with patches of LDPE in the sample.
5) Compared to rice husk, bagasse can effectively serve as a preferred substitute for wood in the production of particle board.

Author contributions: Conceptualization, JA and TRT; methodology, ADA; software, JA; validation, AS, SAL and AKR; formal analysis, JA; investigation, TRT; resources, AS; data curation, TRT; writing—original draft preparation, JA; writing—review and editing, SAL; visualization, AKR; supervision, JA; project administration, ADA; funding acquisition, TRT. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful to Tertiary Education Trust Fund (TETFund) for the grant (TETFUND/TSU/2023/IBR) allocated to this research.

Conflict of interest: The authors declare no conflict of interest.

References

1. Hassan BB, Awopetu OO. Production and characterization of particle boards from common agro wastes in Nigeria. International Journal of Innovative Science and Research Technology. 2019; 4(1): 637-642.
2. Rivela B, Moreira MT, Muñoz I, et al. Life cycle assessment of wood wastes: A case study of ephemeral architecture. Science of The Total Environment. 2006; 357(1-3): 1-11. doi: 10.1016/j.scitotenv.2005.04.017
3. Saeed HSS, Syamsir A, Abu Bakar MS, et al. A Review of Non-wood Lignocellulose Waste Material Reinforced Concrete for Light-weight Construction Applications. Pertanika Journal of Science and Technology. 2024; 32(3): 979-1001. doi: 10.47836/pjst.32.3.01
4. Mathura F, Maharaj R. Non-wood Plants as Sources of Cellulose for Paper and Biodegradable Composite Materials: An Updated Review. Current Materials Science. 2024; 17(4): 321-335. doi: 10.2174/2666145417666230701000240
5. Morasilp D, Sangkakool T. Process optimization and material characterization of fiberboards produced from pineapple leaf waste. Journal of Material Cycles and Waste Management. 2024; 26(3): 1480-1489. doi: 10.1007/s10163-024-01899-6
6. Nakrani D, Tiwari MK, Wani T, et al. Characterization of combustion of hardwood and softwood through experimental and computer simulations. Journal of Thermal Analysis and Calorimetry. 2023; 148(15): 7727-7745. doi: 10.1007/s10973-023-12261-7
7. Kumar S, Rawat D, Singh B, et al. Utilization of bamboo resources and their market value in the western Himalayan region of India. Advances in Bamboo Science. 2023; 3: 100019. doi: 10.1016/j.bamboo.2023.100019
8. Asamoah O, Kuittinen S, Abrefa Danquah J, et al. Assessing Wood Waste by Timber Industry as a Contributing Factor to Deforestation in Ghana. Forests. 2020; 11(9): 939. doi: 10.3390/f11090939
9. Nepal P, Johnston CMT, Ganguly I. Effects on Global Forests and Wood Product Markets of Increased Demand for Mass Timber. Sustainability. 2021; 13(24): 13943. doi: 10.3390/su132413943
10. Ganaie TA, Jamal S, Ahmad WS. Changing land use/land cover patterns and growing human population in Wular catchment of Kashmir Valley, India. GeoJournal. 2020; 86(4): 1589-1606. doi: 10.1007/s10708-020-10146-y
11. Ke S, Qiao D, Zhang X, et al. Changes of China's forestry and forest products industry over the past 40 years and challenges lying ahead. Forest Policy and Economics. 2021; 123: 102352. doi: 10.1016/j.forpol.2020.102352
12. Gonzalez-Garcia S, Ferro FS, Lopes Silva DA, et al. Cross-country comparison on environmental impacts of particleboard production in Brazil and Spain. Resources, Conservation and Recycling. 2019; 150: 104434. doi: 10.1016/j.resconrec.2019.104434
13. Ojewumi ME, Ojewumi EO, et al. Production of Particleboard from Agricultural Waste - A Sustainable Approach to Waste Management. Journal of Sustainable Materials Processing and Management. 2023; 3(2). doi: 10.30880/jsmpm.2023.03.02.007
14. Sylvani MM. Development of Particle Boards with Fillers from Various Kinds of Wood Scraps and Agricultural Residues Using Binders. PROIROFONIC. 2024; 1(1): 291-300.
15. Auriga R, Borysiuk P, Auriga A. An attempt to use „Tetra Pak" waste material in particleboard technology. Annals of WULS, Forestry and Wood Technology. 2021; 114: 70-75. doi: 10.5604/01.3001.0015.2376
16. Acda MN, Cabangon RJ. Termite resistance and physico-mechanical properties of particleboard using waste tobacco stalk and wood particles. International Biodeterioration & Biodegradation. 2013; 85: 354-358. doi: 10.1016/j.ibiod.2013.08.019
17. Atoyebi OD, Aladegboye OJ, Fatoki FO. Physico-Mechanical Properties of Particle Board made from Coconut Shell, Coconut Husk and Palm Kernel Shell. IOP Conference Series: Materials Science and Engineering. 2021; 1107(1): 012131. doi: 10.1088/1757-899x/1107/1/012131
18. Xu J, Widyorini R, Kawai S. Properties of kenaf core binderless particleboard reinforced with kenaf bast fiber-woven sheets. Journal of Wood Science. 2005; 51(4): 415-420. doi: 10.1007/s10086-004-0672-9
19. Paridah MT, Juliana AH, El-Shekeil YA, et al. Measurement of mechanical and physical properties of particleboard by hybridization of kenaf with rubberwood particles. Measurement. 2014; 56: 70-80. doi: 10.1016/j.measurement.2014.06.019
20. Juliana AH, Paridah MT, Rahim S, et al. Properties of particleboard made from kenaf (*Hibiscus cannabinus* L.) as function of particle geometry. Materials & Design. 2012; 34: 406-411. doi: 10.1016/j.matdes.2011.08.019
21. Tabarsa T. Producing Particleboard Using of Mixture of Bagasse and Industrial Wood Particles. Key Engineering Materials. 2011; 471-472: 31-36. doi: 10.4028/www.scientific.net/kem.471-472.31
22. Ghalehno MD, Nazeriasn M. Physical and mechanical properties of particleboard from roselle (*Hibiscus sabdariffa*) stalks

and eucalyptus (*Eucalyptus camaldulensis*) wood particles. Wood Material Science and Engineering. 2012; 7(1): 25-29. doi: 10.1080/17480272.2011.647070
23. Hidayat H, Keijsers ERP, Prijanto U, et al. Preparation and properties of binderless boards from *Jatropha curcas* L. seed cake. Industrial Crops and Products. 2014; 52: 245-254. doi: 10.1016/j.indcrop.2013.10.024
24. Guler C, Copur Y, Tascioglu C. The manufacture of particleboards using mixture of peanut hull (*Arachis hypoqaea* L.) and European Black pine (*Pinus nigra* Arnold) wood chips. Bioresource Technology. 2008; 99(8): 2893-2897. doi: 10.1016/j.biortech.2007.06.013
25. Guntekin E, Karakus B. Feasibility of using eggplant (*Solanum melongena*) stalks in the production of experimental particleboard. Industrial Crops and Products. 2008; 27(3): 354-358. doi: 10.1016/j.indcrop.2007.12.003
26. Parameswaran B. Biotechnology for Agro-Industrial Residues Utilisation. Springer Dordrecht; 2009.
27. Akshaya V, Akila I, Murali R, et al. Rice Straw Biomass and Agricultural Residues as Strategic Bioenergy: Effects on the Environment and Economy Path with New Directions. In: Bioenergy: Impacts on Environment and Economy. Springer Nature Singapore; 2003. pp. 139-164.
28. Salmah H, Koay S, Hakimah O. Surface modification of coconut shell powder filled polylactic acid biocomposites. Journal of Thermoplastic Composite Materials. 2012; 26(6): 809-819. doi: 10.1177/0892705711429981
29. Abutu J, Lawal SA, Ndaliman MB, et al. Effects of process parameters on the properties of brake pad developed from seashell as reinforcement material using grey relational analysis. Engineering Science and Technology, an International Journal. 2018; 21(4): 787-797. doi: 10.1016/j.jestch.2018.05.014
30. Lekshmi MS, Vishnudas S, Anil KR. Lignocellulosic materials as reinforcement and replacement for binders in masonry mortar. Construction and Building Materials. 2021; 282: 122607. doi: 10.1016/j.conbuildmat.2021.122607
31. Suleiman IY, Aigbodion VS, Shuaibu L, Shangalo M. Development of eco-friendly particleboard composites using rice husk particles and gum Arabic. Journal of Materials Science and Engineering with Advanced Technology. 2013; 7(1): 75-91.
32. Mohan-Kumar K, Naik V, Waddar SS, et al. Mechanical and Water Absorption Characterization of Mango Seed Shell/Epoxy Composite for Low Load Carrying Structures. International Journal of Polymer Science. 2023; 2023: 1-15. doi: 10.1155/2023/9976409
33. Pang JC, Li SX, Wang ZG, et al. Relations between fatigue strength and other mechanical properties of metallic materials. Fatigue & Fracture of Engineering Materials & Structures. 2014; 37(9): 958-976. doi: 10.1111/ffe.12158
34. Yang S, Galih NM, Kim J, et al. Physical and mechanical properties of particleboard mixed with waste ACQ-treated wood. Journal of Material Cycles and Waste Management. 2023; 26(1): 410-420. doi: 10.1007/s10163-023-01837-y
35. Chandran A, Ismail A, Charles B, Thejal TT. Particle board using rice husk and coconut fibre. Sustainability, Agri, Food and Environmental Research. 2024; 12(1).
36. Krumins JA, Vamza I, Dzalbs A, et al. Particle Boards from Forest Residues and Bio-Based Adhesive. Buildings. 2024; 14(2): 462. doi: 10.3390/buildings14020462
37. Moi SC, Pal PK, Bandyopadhyay A, et al. Determination of Tungsten Inert Gas Welding Input Parameters to Attain Maximum Tensile Strength of 316L Austenitic Stainless Steel. Strojnícky casopis—Journal of Mechanical Engineering. 2018; 68(3): 231-248. doi: 10.2478/scjme-2018-0037
38. Anugraha RA, Wiraditya MY, Iqbal M, et al. Application of Taguchi Method for Optimization of Parameter in Improving Soybean Cracking Process on Dry Process of tempeh Production. IOP Conference Series: Materials Science and Engineering. 2019; 528(1): 012070. doi: 10.1088/1757-899x/528/1/012070
39. Abutu J, Lawal SA, Ndaliman MB, et al. Production and characterization of brake pad developed from coconut shell reinforcement material using central composite design. SN Applied Sciences. 2019; 1(1). doi: 10.1007/s42452-018-0084-x
40. Kuo Y, Yang T, Huang GW. The use of a grey-based Taguchi method for optimizingmulti-response simulation problems. Engineering Optimization. 2008; 40(6): 517-552.
41. Baharuddin MNM, Zain NM, Harun WSW, et al. Development and performance of particleboard from various types of organic waste and adhesives: A review. International Journal of Adhesion and Adhesives. 2023; 124: 103378. doi: 10.1016/j.ijadhadh.2023.103378
42. Malaki M, Fadaei Tehrani A, Niroumand B, et al. Wettability in Metal Matrix Composites. Metals. 2021; 11(7): 1034. doi: 10.3390/met11071034
43. de Barros Filho RM, Mendes LM, Novack KM, et al. Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. Industrial Crops and Products. 2011; 33(2): 369-373. doi:

10.1016/j.indcrop.2010.11.007

44. Pai A, Rodriguez-Millan M, Beppu M, et al. SS. Experimental techniques for performance evaluation of shielding materials and configurations subjected to Blast and Ballistic impacts: A State-of-the-Art Review. Thin-Walled Structures. 2023; 191: 111067. doi: 10.1016/j.tws.2023.111067
45. Suherman H, Dweiri R, Sulong AB, et al. Improvement of the Electrical-Mechanical Performance of Epoxy/Graphite Composites Based on the Effects of Particle Size and Curing Conditions. Polymers. 2022; 14(3): 502. doi: 10.3390/polym14030502