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Physical-Mechanical properties of wood based composite reinforced with recycled polypropylene and cowpea (Vigna unguiculata Walp.) husk

Esther Nneka Anosike-Francis [a,*], Ifeyinwa Ijeoma Obianyo [a], Oyeyemi Wasiu Salami [b], Gina Odochi Ihekweme [a,c], Michael Ikpi Ofem [d], Abel Olajide Olorunnisola [e], Azikiwe Peter Onwualu [a]

[a] African University of Science and Technology (AUST), Km 10 Airport Road, Galadimawa Roundabout, Abuja 900109, Nigeria
[b] Department of Polymer Technology, Nigerian Institute of Leather and Science Technology, Zaria 810106, Kaduna, Nigeria
[c] Department of Engineering Infrastructure, National Agency for Science and Engineering Infrastructure, Garki Abuja P.M.B 391, Nigeria
[d] Department of Mechanical Engineering, Cross River University of Technology, Calabar 540252, Nigeria
[e] Department of Wood Products Engineering, University of Ibadan, Ibadan 200132, Oyo State, Nigeria

A R T I C L E I N F O

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A B S T R A C T

The need for a sustainable environment and biomass valorization has encouraged research on the recycling of agro and industrial wastes into roofing tiles, ceiling boards, particleboards and furniture. In this study, eco-friendly panels were produced from cowpea husk (CPH), wood chips (WC) and recycled polypropylene (rPP) at different CPH/WC weight percentages and a fixed weight of rPP as binder. The panels were produced by hot compression molding at 150 °C under 2.5 MPa and tested for mechanical (impact strength, modulus of rupture (MOR), modulus of elasticity (MOE)) and physical properties (water absorption (WA), thickness swelling (TS) and density). Fourier transform infra-red spectroscopy (FTIR) was used to study the functional groups in the composite board and raw materials used in addition to the chemical composition. Grey relational analysis was used to optimize performance to a single response, optimal performance was achieved with 80% WC and 20% CPH giving 9.41% water absorption, 15.28% thickness swelling, 1137 kg/m^3 density, 0.127 J/mm impact, MOR of 17.96 MPa and MOE of 741.56 MPa. The physical properties evaluated satisfy the American National Standards Institute (ANSI) A 208.1 standard and confirms that the CPH, WC and rPP mixture can be used for the production boards with good dimensional stability and/or for use in applications where load bearing is not required in the construction industry such as ceiling boards and wall claddings.

1. Introduction

Environmental protection, waste management, forest preservation and the need for renewable energy have all inspired recycling research in diverse industries in the direction of a circular economy (Maraveas, 2020; Awasthi et al., 2021). Good recyclable materials include agricultural biomass (Hills et al., 2020; Foong et al., 2020), industrial wastes (Azambuja et al., 2018) and plastics (Kaur et al., 2018). The global agricultural residues generated per annum is approximately 3.7 × 10^9 tons (Eriksen et al., 2014), while over 5 trillion plastic pieces weighing over 250,000 tons find their way into the marine environment (Eriksen et al., 2014). The volume of these waste materials underscores the need to valorize them (Solis and Silveira, 2020; Almeshal et al., 253 (2020).). An effective way of valorizing agricultural residue and plastic wastes is by recycling them into composite materials for sustainable building applications (Azeko et al., 2016; Ijeoma Obianyo et al., 2021; Obianyo et al., 263 (2020); Ojo et al., 2019). One of these building applications is in the production of panels or boards; a material created by impregnating natural wood fibers into a polymer matrix. They are regarded as among the most resistant wood industry materials in comparison to conventional construction boards, and they have high ecological, environmental, and sustainable value. Many of such panels or boards have found applications in a variety of infrastructure, including doors, roofing, flooring, fencing, and wall cladding (Raj, 2022). Moreso, they have a high market acceptance due to their properties and natural durability, allowing them to replace wood in outdoor and particleboards in indoor environments (Taufiq et al., 2018).

Particleboards (PBD) are extensively used in the construction

* Corresponding author.
E-mail address: eanosike@aust.edu.ng (E. Nneka Anosike-Francis).

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industry, with a 13% yearly increase between 2014 and 2018 (FAO, 2020). The manufacture of PBD has over the years metamorphosed to the use of lignocellulosic materials and recycled plastic as adhesive rather than industrial wood residues and formaldehyde binders. This use of recycled waste (biomass and thermoplastics) improves production efficiency by reducing imports of virgin thermoplastics and contributes to the reduction of environmental pollution caused by such waste. Furthermore, companies can provide a sustainable destination for their waste, and society benefits from high-quality PBD with a wide range of applications that can meet their needs. For example Fitri N. and Ismail I. studied the physical and chemical properties of PBD made of rice straw particle and waste polypropylene (PP) as adhesive, with PP content of upto 70%. The results produced boards with density and thickness swelling that met the requirement for Indonesian Standard of particleboard (Fitri and Mursal, 1460 (2020).). Kuka et al. investigated how different size fractions of thermally modified wood particles influence mechanical and water resistance properties of a wood plastic composite (WPC) at 50 wt-% wood particles and 50 wt-% PP. The results showed that the particle size had a significantly smaller influence on the mechanical properties of the WPC when compared to WPC with unmodified wood particles (Kuka et al., 2018). Gozdecki et al. evaluated the mechanical and physical properties of the composites made by injection moulding from milled particleboard and PP with respect to the content of particles derived from PBD and coupling agent addition. Results obtained did not differ significantly from those of composites of virgin industrial wood particles used for manufacturing the PBD and were also comparable with the properties of typical WPC with wood flour (Gozdecki et al., 2015).

The suitability of mango seed shells for PBD production using recycled high-density polyethylene (RHDPE) as binder was studied by Abolaji et al. (Abolaji et al., 2017) for various mix ratios resulting in composite boards with an MOR of 11.49 MPa, an MOE of 2450 MPa, an IB of 0.58 MPa and a hardness value of 5.17 HBR. Despite all the various literature, there is little or no reseach on the use of cowpea husk and wood particles bonded in recycled polypropylene in panel production. Cowpea husks (CPH) is the byproduct of cowpea processing which is one of the vital legumes of sub-Saharan African origin grown in tropical lowlands and additionally warm temperate regions. According to the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2020), Nigeria is the highest world producer of cowpea, with 40% of total world production, followed by Niger 32% and Burkina Faso 8%, while the International Institute for Tropical Agriculture (IITA) in 2017 estimated that>7.4 million tons of dried cowpea were produced worldwide, with Africa producing nearly 7.1 million. Nigeria iis the largest producer and consumer of copea and accounts for 48% of production in Africa and 46% worldwide. In spite of the abundance of cowpea residues, they are yet to be harnessed in Nigeria for the production of value-added products as they are is often burnt into ashes or dumped as solid waste, with little being used as animal feed and hence the motivation for this present research to valorise. Appropriate utilization of this residue can scale back the emission of greenhouse gas, eliminate the menace caused by indiscriminate waste disposal and improve the economic base of Nigeria through the valorization of biomass. The main aim of the study was to explore the feasibility and suitability of cowpea husk as a partial or total replacement of wood in the laboratory production of panels or boards using rPP as binder. The produced boards contained 33.33% rPP flakes and were analysed using standards in accordance with different ASTM standards for particle boards. The amount of rPP used in the production of the boards also qualified them as WPC. Hence the use of WPC and PBD in this work. The specific objectives were to: synthesize a bio-composite made up of wood chips, cowpea husk and recycled polypropylene; determine the physical and mechanical properties of the composite and compare with established standard for particleboard.

Table 1
Experimental design of the boards.

S/N	Sample Code	Weight % of CPH	Weight % of WC
1	WC100	0	100
2	WC90	10	90
3	WC80	20	80
4	WC70	30	70
5	WC60	40	60
6	WC50	50	50
7	WC40	60	40
8	WC30	70	30
9	WC20	80	20
10	WC10	90	10
11	CPH100	100	0

2. Materials and methods

2.1. Cowpea Husk, wood chips and polypropylene processing

Industrial wood chips (WC) consisting of an equal proportion of mixed hardwood species of pinewood (Pinus), opepe (Nauclea diderrichii), mahogany (Swietenia macrophylla) and iroko (Milicia excelsa) were collected from a saw mill at Jabi, Abuja, Nigeria. Cowpea husks (Vigna unguiculata walp.) (CPH) were obtained from a farm in Nassarawa State, North Central, Nigeria, immediately after cowpea harvest. CPH were first cleaned of dust and dirt. Both the CPH and WC were crushed in a size reduction machine and were then classified in a horizontal screen shaker. For the WC, particles that passed through 3 mm but remained in the 2.36 mm sieve was used while the CPH utilized particles that passed through 2.36 for the particleboard production. Particles were oven dried at 55 °C to reach the target moisture content of 3%.

The recycled polypropylene (rPP) flakes used in this experiment was obtained from the recycling unit (Department of Polymer Technology, Nigerian Institute of Leather and Science Technology, Samaru, Zaria). It is a homopolymer, recyclable, reusable with a density of 0.912 g/cm^3 and melt flow index of 8 g/10 min (230° C/2160 g). It consists of disposable plates recovered after consumption, which were washed, dried and passed through a granulator of an average outlet diameter of 12 mm. The choice of rPP as the matrix material for the composite development is a result of its mass availability as waste in the environment, its unfavorable effect relating to nonbiodegradability and the sustainability requirement of materials sought for in recent times. It also reduces the cost of the particleboard.

For composite preparation, the calculated weights of CPH and WC, as shown in Table 1, were measured with an Ohaus electronic analytical laboratory weighing balance and stored in sealed cellophane bags at room temperature. Each composition contained 33.33% rPP flakes. The bags were labeled according to compositions for easy identification.

2.2. Fabrication of recycled Polypropylene, wood chips and cowpea husks composite

The CPH, WC and rPP samples were compounded separately for each composition on a two-roll mill manufactured by Reliable Rubber and Plastic Company (North Bergen, NJ, USA) according to the experimental design in Table 1. The CPH-WC fibers and the rPP flakes were compounded on the mill at 170 °C at a speed of 1.133 rpm. The mix was carefully placed in a metallic mold of dimensions 110 mm × 110 mm × 3.2 mm. The mat was pressed together on an electrically heated hydraulic press at a temperature of 150 °C under 2.5 MPa for a period of 5 min. A foil paper was placed in the metallic mold to aid the ease of removal of the developed composite from the mold after the curing process. Samples were cooled at room temperature for 7 min in a hydraulic press and set aside for 24 h, after which they were cut to shapes of three each for the various physical and mechanical tests. Three replicates were evaluated for each of the evaluated properties, totaling 33

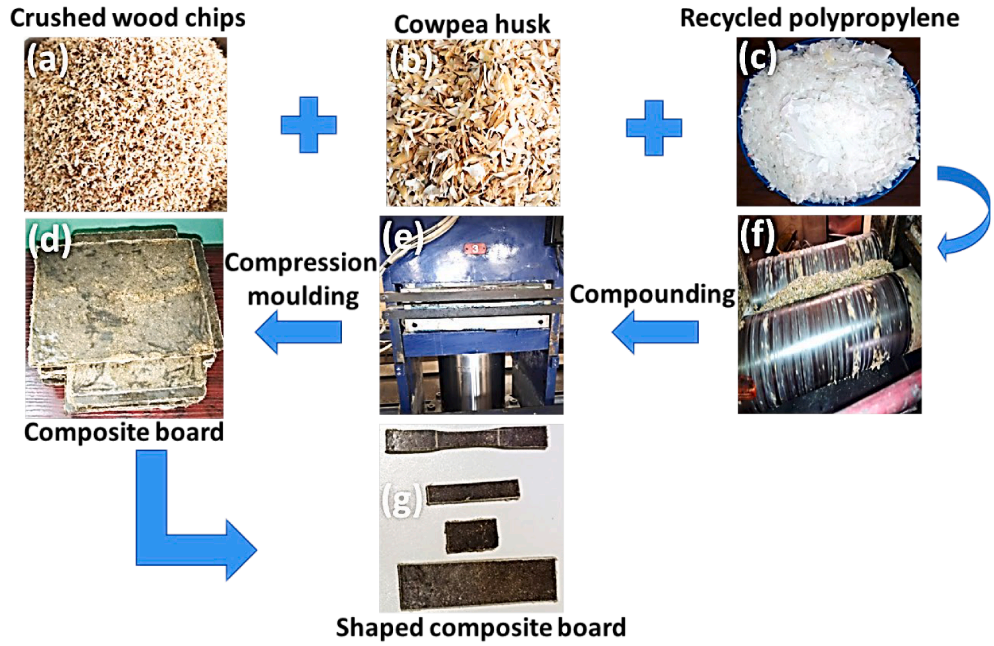

Fig. 1. Process of composite production: (a) crushed wood chips; (b) cowpea husk; (c) recycled polypropylene; (d) compounding of composite in two-row mill; (e) compression molding machine; (f) produced composite boards; (g) cut composite board.

test samples.The average values of each batch were used for the calculations. The process for composite fabrication is shown in Fig. 1.

2.3. Chemical and Physico-chemical analysis

The CPH and WC were investigated for cellulose, hemicellulose and lignin using a Fourier-transform infrared spectroscopy (FTIR). The FTIR was used to characterize the hydrogen bonds in cellulose, lignin and hemicellulose. Analytical-grade potassium bromide (KBr) obtained from Guangzhou Jinjuada Chemical Reagent Company Limited was mixed thoroughly in an agate mortar with the powdered form of CPH sample in the ratio of 10:1 and pressed into pellets using a 10-ton press. Optimal spectra in the region of 4000–500 cm^{-1} were obtained at high resolution, and several scans were recorded with the Fourier-transform infrared spectrometer (Thermo Scientific Equipment, Model: Nicolet IS5, made in the USA).

The chemical composition of CPH and WC was also determined using the method described by (Chaydarreh et al., 2021). This requires the isolation of each fraction through sequential phases of hydrolysis and extraction (Rowell et al., 2012). The extractive content was first determined by extraction of particles using Soxhlet extractor method. Then the extracted dried CPH was transferred in 1.4 wt% $NaClO_2$ at 70 ℃ for 5 h with pH value around 5–6 for determination of lignin content. The delignified product was immersed in 5 wt% NaOH at 90 ℃ for 4 h to determine hemicellulose content. The product obtained was treated with a concentrated 72 wt% H_2SO_4 at 60 ℃ for 6 h and 4 wt% H_2SO_4 at 27 °C for 4 h to determine cellulose content. The ash measurement test is performed in accordance with the ASTM E1755-61 standard. The ash content was determined by heating the CPH at 500 ℃ for 2 h in the muffle furnace. The difference in weight between the burned and unburned fibers is used to predict the amount of ash present in the fiber. The conventional weight loss method is used to determine the quantity of moisture content. The weight differential of the fiber is measured in that circumstance, which represents the amount of moisture content present in the fiber. The basic density of CPH was measured using the method as described by (Narciso et al., 2021) (water displacement method) with little modification in measurements. Two grams of the sample was completely immersed in water and the volumetric displacement was noted. The ratio of weight and volume presented the density of the sample.

2.4. Morphological examination

The structure of representative samples were visualized by scanning electron microscope (SEM) (Carl Zeiss SEM Model: evo10LS-EDAX, made in Germany) at a very high magnification in order to observe the distribution and interaction of CPH and WC in rPP matrix. Samples were coated with gold nanoparticles in a mini sputter coater to prevent the samples from charging and reflection.

2.5. Physical property determination

The physical properties of the fabricated boards was determined according to ASTM D-1037 (ASTM D-, 2016). These include: density, water absorption (Wa) and thickness swelling (TS). The samples were cut to dimensions of 4 × 3 × 0.32 cm of three for each batch for physical test.

2.4.1. Density test

The density (ρ) of the produced samples was determined by the average density of each batch of produced samples. The weight of each sample was taken using a digital weighing balance and recorded.

2.4.2. Water absorption test

The water absorption test was carried out at room temperature to determine the variation in mass due to the amount of water the board can absorb after a period of time until a constant weight is obtained. The mass of the samples was measured with a digital scale with a sensitivity of 0.0001 and recorded before immersing into water. The test was performed at room temperature for 2, 24, 48 and 72 h to determine the effect of prolonged immersion in water. Measurements of the soaked samples were taken after 2, 24, 48 and 72 h to note any increase in mass and percentage water absorption obtained. Three samples per panel was tested.

2.4.3. Thickness swelling test

This test was used to determine the effect of water on the thickness of the samples over a period of time. The sample thickness before and after

Table 2
Experimental result of the signal-to-noise ratio values.

Run	Weight % of WC	S/N RATIOS OF RESPONSES MOE (MPa)	MOR (MPa)	Impact (MPa)	% WA after 24 h	% TS after 24 h	Density Kg/m^3
1	100	55.2840	23.0763	−17.0156	−19.3976	−18.7904	−60.8751
2	90	51.8050	23.4287	−18.3443	−15.4903	−18.3920	−60.6845
3	80	57.4029	25.0861	−17.9239	−19.4718	−23.6825	−61.1152
4	70	56.0270	21.7981	−17.9239	−11.9977	−19.1138	−60.9921
5	60	55.6341	23.3876	−18.0618	−19.9039	−19.3697	−60.8908
6	50	49.2536	15.8057	−16.9542	−20.4486	−20.9844	−60.7166
7	40	50.6671	16.8522	−20.0873	−16.4040	−18.3606	−60.3989
8	30	53.2727	20.3906	−22.3837	−27.6115	−24.5114	−61.0769
9	20	55.5173	20.0087	−20.1755	−16.2449	−17.9855	−60.5796
10	10	55.0746	22.0966	−19.0156	−22.0945	−24.0824	−60.7645
11	0	59.1294	24.0443	−16.8933	−16.8397	−17.0861	−61.0462
	Maximum	59.1294	25.0861	−16.8933	−11.9977	−17.0861	−60.3989
	Minimum	49.2536	15.8057	−22.3837	−27.6115	−24.5114	−61.1152

immersion in water was measured with a digital Vernier caliper of 0.01 sensitivity. Samples were immersed for 2, 24, 48 and 72 h. The value of thickness swelling was calculated and recorded.

2.6. Mechanical properties determination

2.6.1. Flexural strength

The Enerpac universal materials testing machine (Cat No.: 261 100KN) was used to carry out the three-point bending test according to the ASTM D-7264 standard of dimensions of 100 × 5 × 3.2 mm, with the sample balanced on two supports and a concentrated load increasing at a rate of 1 mm/min applied at the center until breakage. A range of 80 mm was used, with a 10 mm overhang on both sides of the support. The bending properties in terms of modulus of rupture (MOR) and modulus of elasticity (MOE) were determined in MPa.

2.6.2. Impact strength test

The impact test was carried out to determine the board's ability to withstand fall or collision with other objects using the Izod impact tester (Resil impactor testing machine) on all the developed composites cut to size 80 × 15 × 3.2 mm in accordance with ISO 180 ASTM D-256 for the Izod impact test. Notched Izod impact is a single-point test that measures a material's resistance to impact from a swinging pendulum. The notched specimen was clamped vertically on the jaw of the machine, and a hammer weight of 1500 N was released from an inclined angle of 240° to the notched sample. The energy exerted to break the sample was read off and recorded. This was carried out for three replicates on each batch and the average used for the calculation.

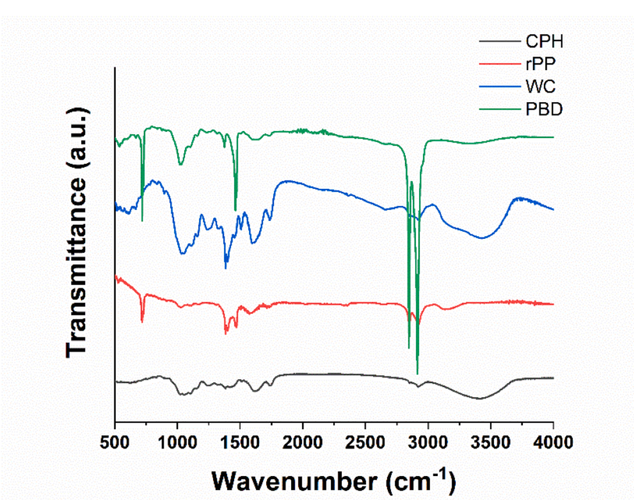

Fig. 2. FTIR spectra of CPH, rPP, WC and PBD.

2.7. Statistical analysis of responses

The individual signal-to-noise (S/N) ratio of experimental values obtained from the mechanical and physical properties examination was calculated using smaller-the-better and larger-the-better quality characteristics, as shown in Equations (1) and (2), respectively. These were used to calculate the signal-to-noise ratios of physical and mechanical properties of the composite materials shown in Table 2. The formulated composites were optimized using a multi-response optimization technique called grey relational analysis (GRA). The GRA technique is used to consolidate all properties that have been considered into a single value that can then be employed in optimization problems as a single characteristic (Kuo et al., 2008). This technique used the S/N values obtained to calculate the grey relational generation, with larger- and smaller-the-better attributes given in Equations (3) and (4), respectively. This is preceded by scaling all performance values to 0 and 1 (reference sequence definition), and then the grey correlation coefficient and grade were calculated using Equations (5) and (6), respectively (Abutu et al., 2018). The final process of GRA was the determination of optimal factors for the single response.

$$Smaller-the\ better: \frac{S}{N} = -10log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

$$Larger-the\ better: \frac{S}{N} = -10log\frac{1}{n}\left(\sum_{i=1}^{n} \frac{1}{y^2}\right) \quad (2)$$

where y is the given factor level combination responses, and n is the number of factor level combinations.

$$Larger\ -the\ better\ attributes\ (\chi_{ij}) = \frac{y_{ij} - y_{-i}}{\bar{y}_i - y_j} \quad (3)$$

$$Smaller\ -the\ better\ attributes\ (\chi_{ij}) = \frac{\bar{y}_{ij} - y_{ij}}{\bar{y}_j - y_{-ji}} \quad (4)$$

(i = 1, 2, 3, …, m and j = 1, 2, 3, …, n) where yi = (yi1, yi2, …, yij, …, yin), yij is the performance value of attribute j of alternative i and $\bar{y}_i$ = max{yij, i = 1, 2, …, m} and y_{-i} = min{yij, i = 1, 2, …, m}.

$$\gamma(\chi_{0j}, \chi_{ij}) = \frac{\Delta_{min} + \beta\Delta_{max}}{\Delta_{ij} + \beta\Delta_{max}}\ (i = 1, 2, \cdots, m\ and\ j = 1, 2, \cdots, n \quad (6)$$

where γ(x0j, xij) is the grey relational coefficient between xij and x0j, Δ_{ij} = x0j – xij, Δ_{min} = min (Δ_{ij}, i = 1, 2, …, m; j = 1, 2, …, n), Δ_{max} = max (Δ_{ij}, i = 1, 2, …, m; j = 1, 2, …, n) and β is the distinguishing

Table 3
Physico-chemical composition of CPH.

Materials	Bulk Density	Ash content (wt.%)	Moisture content (wt.%)	Extractives (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)	Cellulose (wt.%)	PH
Cowpea husk	463.1 ± 23.15	9.23 ± 0.39	4.30 ± 0.19	11.80 ± 0.56	36.30 ± 1.80	31.80 ± 1.50	20.10 ± 1.00	6.0 ± 0.29
Wood chips	600 ± 0.28	–	7.19 ± 0.33	10.42 ± 0.49	45.74 ± 2.26	29.89 ± 1.47	14.67 ± 0.70	7.2 ± 0.28

Values represent the standard deviation.

coefficient,$\beta \in[0,1]$. The aim of the distinguishing coefficient (β) is to compress or expand the range of the grey relational coefficient, and 0.5 is the widely accepted value (Abutu et al., 2018). Kuo et al. (Kuo et al., 2008) reported that after grey relational generation, Δ_{max} will be equal to 1, and Δ_{min} will be equal to 0.

$$\varphi(x_0, x_i) = \sum_{j=0}^{n} w_j \beta(x_{0j}, x_{ij}) \; ; (i = 1, 2, 3 \cdots\cdots\cdots m) \quad (7)$$

w_j represents the weight of attribute j, which is usually dependent on the judgments of the decision maker or the structure of the proposed problem. Ref. Kuo et al. (Kuo et al., 2008) stated that $\sum_{j=1}^{n} w_j = 1$.

Results and discussion

3.1. Chemical and Physico-chemical analysis

The FTIR of the raw materials and sample produced are presented in Fig. 2. The absorption band observed at 3131–3424 cm^{-1} corresponds to the stretching vibration of the OH^- groups for all the four samples (Wang et al., 2017). The bands at 2828–2937 cm^{-1} were assigned to C–H stretching vibrations while the band at 2426 cm^{-1} for the rPP is assigned to S-H in-plane deformation vibration which is attributed to the contamination in the rPP (Morent et al., 2008). Peaks observed at 2918 and 2849 cm^{-1} are due to CH_2 asymmetric and symmetric stretching vibrations respectively. The double peaks at ~ 1610–1760 cm^{-1} band were assigned to the C = O stretching of the acetyl groups (Larkin, 2017). In the WC sample the band at 1510 cm^{-1} is assigned to the aromatic skeletal vibration of lignin (Wang et al., 2014), and the weak peak at 1260 cm^{-1} and 1281 cm^{-1} corresponds to C–O stretching of lignin and C = O in carboxylic acids in the CPH (Guyo and Moyo, 2017). The fingerprint region ~ 1500 cm^{-1} for all samples exhibited a number of structural bonds for the material with C-OH out-of-plane bending at 620 and 624 cm^{-1} (Wang et al., 2014).

The rPP peaks at 1463 cm^{-1} corresponds to CH_3 asymmetric deformation vibrations while 1398 cm^{-1} is due to CH_3 symmetric deformation vibrations (Morent et al., 2008; Mylläri et al., 2015). The peak at 1460 cm^{-1} is caused by CH_3 asymmetric deformation vibrations or CH_2 scissor vibrations; while the peak at 1378 cm^{-1} is due to CH_3 symmetric deformation vibrations (Larkin, 2017). The spectrum of the rPP also shows numerous small peaks in the wavenumber range 1200–750 cm^{-1}.

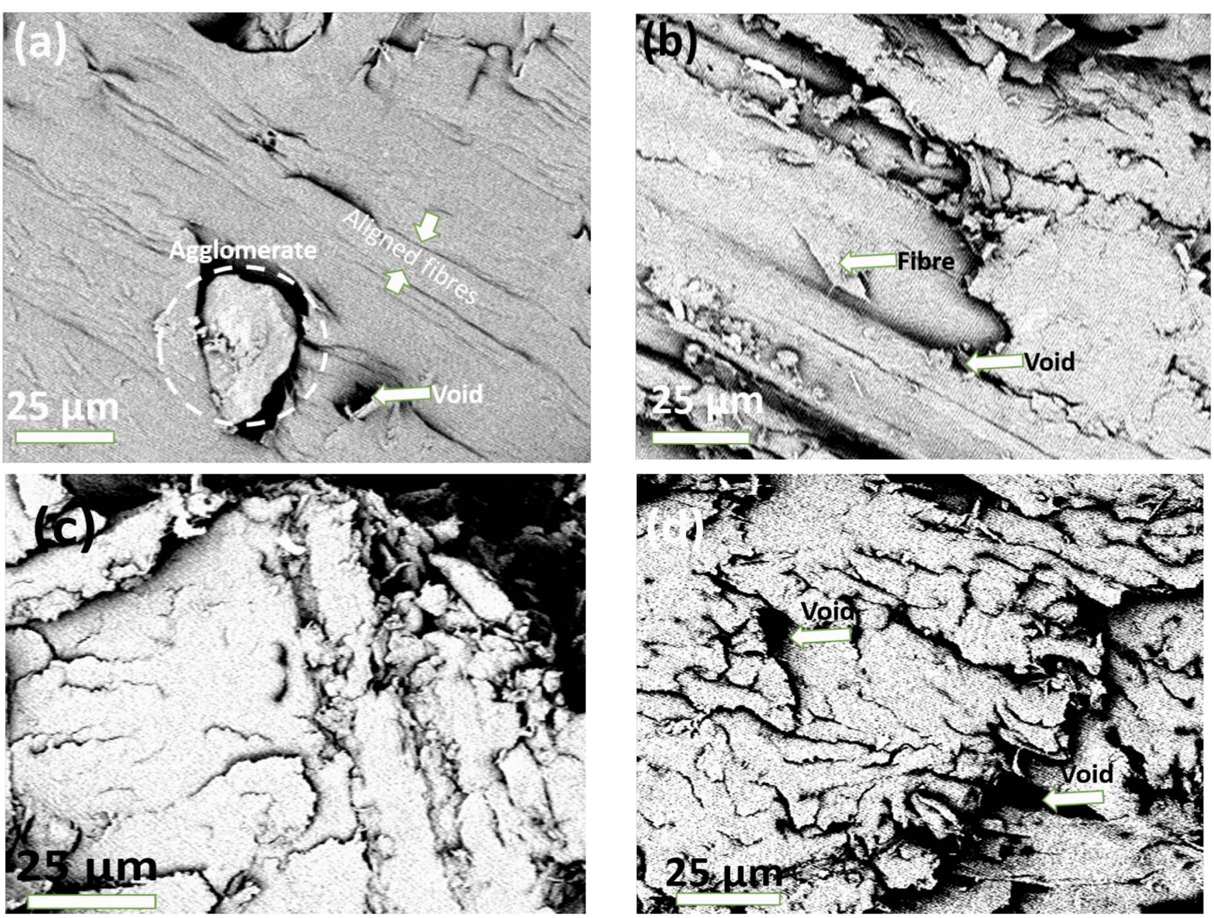

Fig. 3. SEM micrographs (1000x magnification) of composites (a), 100WC (b), WC50 (c), WC80 (d), CPH100.

Table 4
Results obtained with standard deviation.

Composition	Density Kg/m^3	TS %	WA %	MOR MPa	MOE MPa	IMPACT J/mm
WC100	1106 ± 54.06	8.7 ± 0.40	9.33 ± 0.41	14.25 ± 0.67	581.03 ± 29.02	0.141 ± 0.005
WC90	1082 ± 53.41	8.31 ± 0.38	5.95 ± 0.25	14.84 ± 0.72	389.27 ± 19.43	0.121 ± 0.004
WC80	1137 ± 56.71	15.28 ± 0.68	9.41 ± 0.44	17.96 ± 0.85	741.56 ± 37.03	0.127 ± 0.004
WC70	1121 ± 55.80	9.03 ± 0.43	3.98 ± 0.15	12.3 ± 0.59	632.92 ± 31.62	0.127 ± 0.004
WC60	1108 ± 54.51	9.3 ± 0.46	9.89 ± 0.45	14.77 ± 0.70	604.93 ± 30.22	0.125 ± 0.005
WC50	1086 ± 53.43	11.2 ± 0.53	10.53 ± 0.51	6.17 ± 0.29	290.19 ± 14.48	0.142 ± 0.005
WC40	1047 ± 53.24	8.28 ± 0.39	6.61 ± 0.31	6.96 ± 0.32	341.47 ± 17.04	0.099 ± 0.002
WC30	1132 ± 56.16	16.81 ± 0.80	24.02 ± 1.10	10.46 ± 0.51	460.93 ± 23.02	0.076 ± 0.001
WC20	1069 53.35	7.93 ± 0.35	6.49 ± 0.29	10.01 ± 0.48	596.85 ± 29.82	0.098 ± 0.002
WC10	1092 ± 53.46	16 ± 0.78	12.727 ± 0.62	12.73 ± 0.61	567.19 ± 28.33	0.112 ± 0.002
CPH100	1128 56.00	7.15 ± 0.32	6.95 ± 0.32	15.93 ± 0.75	904.63 ± 45.21	0.143 ± 0.005

Below 1000 cm^{-1} there is stretching vibration due C-CH at 729 and a deformation vibration due to CH_2 at 718 cm^{-1} (Mylläri et al., 2015). The FTIR evaluation of the particleboard shows similar behaviour as the raw materials used it with higher intensity when compared with the other samples. The peaks are located at 2845 and 2915 cm^{-1} corresponding to C-CH_3 stretching vibration from the cellulose in WC and CPH while the peaks 1473 cm^{-1} is attributed to CH_2 out of phase bending vibration from rPP [65]. The peaks at 1379 and 1036 cm^{-1} correspond to CH deformation vibration in the cellulose and CH_2 twisting vibration respectively [65]. Between 717 and 724 cm^{-1} appears intense and weak peaks assigned to the ring in-phase and semi-circle vibration due to cellulose. There is a significant similarity in several peaks of the composite and raw materials suggesting that formation of the composite does not totally alter the chemical properties of the raw materials.

The chemical composition of natural fibers has a significant impact on mechanical, fire resistance, resilience, and biodegradability features. The results of CPH and WC's physico-chemical characterisation are shown in Table 3. Both revealed a higher amount of hemicellulose similar amount of lignin, and a lower content of cellulose as both coffee husk and hulls (Bekalo and Reinhardt, 2010). The mechanical qualities of particleboards are closely connected to the amount of cellulose in the sample. Lower cellulose concentration has a considerable detrimental impact on mechanical characteristics. High hemicellulose concentration reduces sample strength by causing micro fibril breakdown and disintegration. Lignin is involved in the adhesion process therefore the higher lignin content is beneficial to bonding capacities (Mahieu et al., 2019).

3.2. Morphological analysis

Fig. 3 shows the micrograph of representative samples. The microscopy images of W100 is shown in Fig. 3a displaying a smooth and homogeneous surface with the presence of voids, agglomerates and the alignment of the the fibres. The presence of the voids could be due to non uniform distribution of the pressure during compacting. This voids could serve as point for crack propagation and may eventually lead to the failure of the sample under continous stress. Fig. 3b displays the morphology of W50 showing a non homogeneous surface with the fibre not fully encapsulated in the polymer. Very large voids are observed which is responsible for the poor mechanical property displayed by the sample. Fig. 3c shows a compact image of the W80 sample with less voids and crevices when compared with W50. The compactness is responsible for the improved mechanical properties. Lastly, Fig. 3d for sample CPH100 displayed similar micrograph as W80 with more voids which could affect the performance of the sample when compared to the others.

3.3. Physical properties

The average results obtained for each batch for the physical and mechanical properties of the composites were tabulated and presented in Table 4.

3.3.1. Density test results

The density of the samples produced in this work ranges from 1047 kg/m^3 to 1137 kg/m^3 and are similar to results obtained by Lopez et al. (Martinez Lopez et al., 244 (2020).) who reported densities between 1050 kg/m^3 and 1100 kg/m^3. It was also observed that the composites exhibited higher densities compared with individual raw materials. The increase in density is attributed to the synergistic effect between the biomass and the rPP. Based on the high density values obtained in this work, we conclude that the composite is suitable as board requirements due to the category of data obtained. All the samples met the ANSI A 208.1 (American National Standards Institute, 1999) standard for high-density particleboard category of above 800 kg/m^3 and JIS.A.5908 (Japanese Industrial Standard Committee, 2003) minimum density value of 800 kg/m^3 and hence will be suitable for wall paneling and flooring.

3.3.2. Water absorption

The water absorption values were calculated to measure the ability

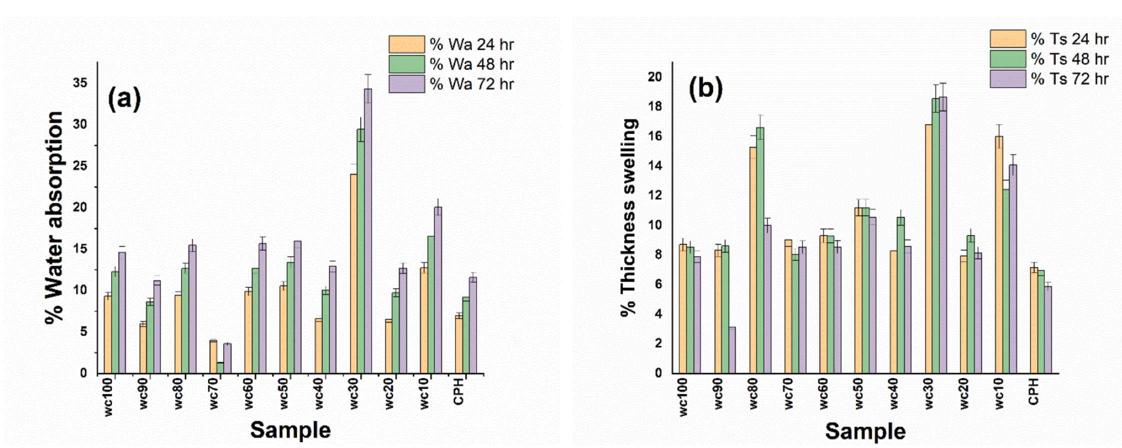

Fig. 4. Effect of time variation on (a) water absorption and (b) thickness swelling.

Table 5
Results of Grey relational generation coefficient (GRC) and grade.

Weight % WC	GREY RELATIONAL COEFFICIENT (GRC) MOE (MPa)	MOR (MPa)	Impact J/mm	% WA after 24 h	% TS after 24 h	Density Kg/m^3	Grey relational grade (GRG)
100	0.5622	0.6978	0.9573	0.4873	0.3936	0.5986	0.6161
90	0.4027	0.7368	0.6542	0.3918	0.3776	0.4540	0.5029
80	0.7409	1.0000	0.7270	0.4896	0.8175	1.0000	0.7958
70	0.6141	0.5853	0.7270	0.3333	0.4075	0.7442	0.5686
60	0.5855	0.7320	0.7014	0.5032	0.4193	0.6148	0.5927
50	0.3333	0.3333	0.9783	0.5215	0.5128	0.4733	0.5254
40	0.3685	0.3604	0.4622	0.4106	0.3764	0.3333	0.3852
30	0.4574	0.4970	0.3333	1.0000	1.0000	0.9034	0.6985
20	0.5775	0.4775	0.4555	0.4072	0.3626	0.4007	0.4468
10	0.5491	0.6082	0.5640	0.5859	0.8964	0.5052	0.6181
0	1.0000	0.8166	1.0000	0.4202	0.3333	0.8384	0.7348

of the produced composites to absorb water after 2, 24, 48 and 72 h as shown in Fig. 4a. There was no measurable increase in mass after 2 h until after 24 h. This could be due to the hydrophobic nature of the rPP. The rate of water absorption is influenced by the type and amount of adhesive, such as polypropylene, which inhibits the absorption of water (Liang et al., 2021). The more adhesive is used, the lower the rate of water absorption by particleboard (Fitri and Mursal, 1460 (2020).). Thus, rPP is an appropriate matrix to diminish water assimilation in particleboard. The result shows that irrespective of the percentage of WC or CPH in the admixture the water absorption of the samples increased with time, as represented in Fig. 4a. This behavior is due to the hydroxyl groups (–OH) present in WC and CPH interacting with water molecules by hydrogen bonding (Kariuki et al., 2020), but because the rPP matrix is hydrophobic, the rate of water absorption is low and in range with other agro-based composites reported in the literature, such as Masturi et al., who produced teak leaf waste/polyurethane composite with a water absorption range from 1.38% to 107.35% (Masturi et al., 2020), and Mirindi et al., who developed macadamia nutshell composite with water absorption range between 9.42 and 38.76% (Mirindi et al., 2021). The water absorption of the samples is in the range of 3.98% to 24.02%. This variation in the water absorption value can be linked to fault zones in the composites capable of influencing the properties of the samples. At 170 °C of manufacturing, combustion and evaporation of water and some gases from the components of the cell wall occur. This inhibits the complete encapsulation of the polypropylene in the filler, creating micro voids (Fig. 3) that favor water transportation (Kaboorani, 2017). Except for WC30, the values of water absorption obtained for the composite boards are low compared to FAO standards for particleboard, which specifies values between 20 and 75% after 24 h. This high water absorption of WC 30 can be attributed to the amorphous hydrophilic hemicellulose as shown in Table 3 or due to press time. Also the CPH and WC fibres were used without applying any water repellant treatment. The general low WA value makes the samples a good alternative for composites boards that need to be subjected to humid environments.

3.3.3. Thickness swelling test

After 2 h of immersion in water, the percentage thickness of samples was practically zero, as also reported by (Fitri and Mursal, 1460 (2020).). A notable difference in thickness occurred at 24 h, after which most samples attained saturation (Fig. 4b). This is observed by a steady thickness at 48 h, as shown in Fig. 4b. Reduction in sample thickness was noticed after 48 h, which implies that after 48 h, some of the particles of the samples began to disintegrate. This disintegration was a result of the weakening of the bonding between the particles of the composites caused by saturation. Hence, the percentage swelling thickness was taken at 24 h. Slight variations in the thickness of the particleboards were observed, which can be due to the ratio of matrix and filler. The variation could also be attributed to the possible non-uniform distribution of the compressive loading during compaction (Akinyemi et al., 2016). Data show that 100% CPH has the lowest thickness swelling of 7.15%, while 30% WC has the highest of 16.81% owing to the high volume of hemicellulose present in the fibres CPH and WC. The Japanese Industrial Standard stipulated that the maximum thickness swelling at 24 h is 12% (Standard, 2003). Thus, sample boards WC10, WC30 and WC80 did not satisfy this condition. But all met the 17% minimum requirement of EN 312 for particleboard type P3 for non-load-bearing panels for use in humid conditions (Committee, 1996).

3.4. Mechanical properties results

The average results and standard deviation of the physical and mechanical properties evaluated are shown in Table 4. The standard deviation indicates that there is high consistency for the data obtained from the density, thickness swelling, water absorption tests, modulus of rupture and impact strength. However, there is huge spread (dispersion) for the data obtained from the modulus of elasticity. This is because the higher the standard deviation, the higher the volatility of the data (higher rate of change in the values of the data) and also the higher variations could be due to measurement device.

3.4.1. Flexural strength results

The average MOR calculated ranged between 6.17 and 17.96 MPa, while the MOE is from 290.19 to 904.63 MPa. The lowest MOR corresponds to the lowest MOE for the particleboard containing 50% wood chips. The introduction of CPH led to a gradual increase in the MOR value and the maximum MOR was obtained at 20% replacement. However, fluctuations were observed in the MOR values as well as the MOE values (Table 4).

This MOR and MOE results' trends are similar to those obtained by (Akinyemi et al., 2016; Pelumi et al., 2018). The decrease observed in the bending performances is due to the randomly oriented materials and non-aligned strands in the board (Han et al., 2007).

This decrease of MOR and MOE were more significant for the boards with lower board densities. The mechanical properties of the boards evaluated appears to be directly proportional to the density with the highest average values for compositions WC80 and CPH100. The low MOE of the boards could be attributed to the raw material compatibility with the rPP binder leading to poor interfacial interaction between the polymeric matrix, wood particle and CPH (Dotun et al., 2018). The low cellulose content in the fibres also inhibits efficient stress transfer between the phases of the material. The MOR of composites WC100, WC90, WC80, WC70, WC60, WC10 and CPH100 are in line with the EN 312–2 standard requirement of 11.5 MPa and ANSI A 208.1 standard of a 12.5 MPa (American National Standards Institute, 1999) for low density panels minimum requirement. The obtained values for samples WC90, WC50, WC40 and WC30 did not meet the minimum acceptable value of MOE (550 MPa) as specified by ANSI A208.1–1999.

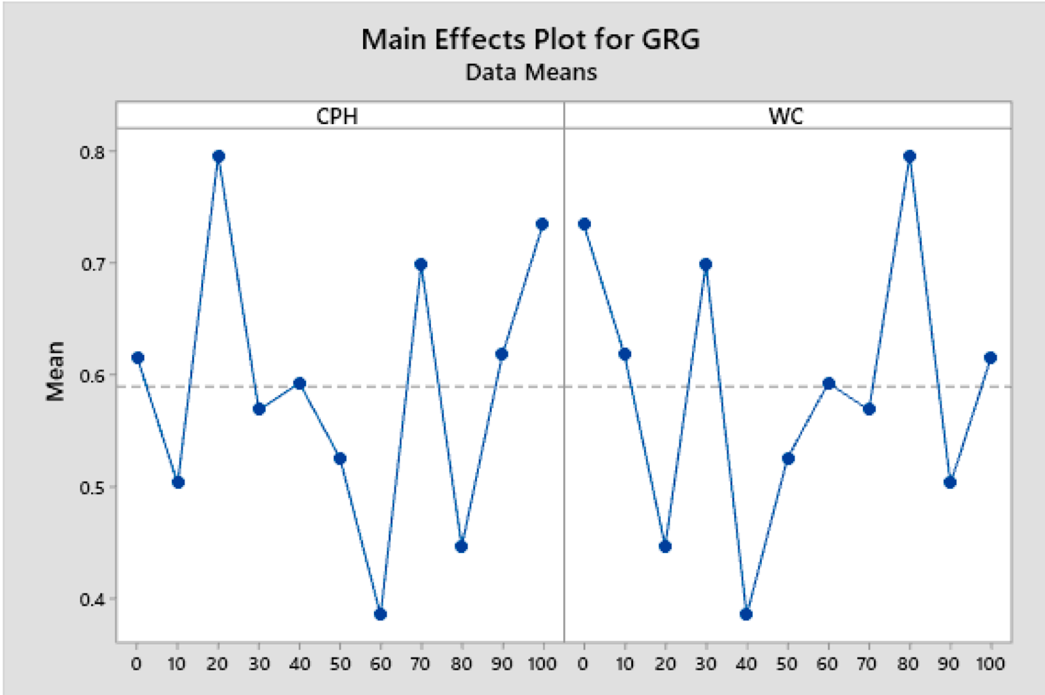

Fig. 5. Main effect plot of optimal level conditions of factors.

Table 6
Optimal result obtained in comparison with some agro-based particleboards in literature.

Raw materials	Resin & content (%)	% WA after 24 hr	% TS after 24 hr	Density (kg/ m^3)	MOR (MPa)	MOE (MPa)	Ref.
Woodchips & cowpea husk	rPP (33)	3.98–12.72	7.15–16.81	1047–1137	6.96–17.96	290.19–904.63	This work
Cassava stalk	UF (67.7–75)	20–43.12	6.26–24.54	1000	2.56–4.0	1075–2367	(Aisien et al., (2015). 10.17159/sajs.2015/20140042.)
Corn cob and Sawdust	UF (30)	106.14–145.15	–	413–486	0.8–1.3	54.418–82.555	(Akinyemi et al., 2016)
Sawdust (Cedrela odorata)	Recycled thermoplastic (20–60)	1–6	1–6	1050–1100	5–24	2120–4050	(Martinez Lopez et al., 244 (2020).)
Brewer's spent grain	UF (8)	22–27	98–108	620	5.77 – 11.9	1537 – 2374	(Klímek et al., 2017)
Corn stalk & woodchips	UF (20)	46.67–63.39	18.54–25.55	700	9.13–14.08	1419–2937	(Guler et al., 2016)
Water melon peels	RLDPE (30–70)	>50	>10	500–700	5.77–11.9	1537–2374	(Idris et al., 2011)
Macadamia Nutshell	Gum arabic (20–50)	9.42–38.76	6.22–28.46	818.60–1219.20	4.20–12.21	1810	(Mirindi et al., 2021)
Saw dust	PET (10–50)	105.94–148.50	11.76–2.92	430.62–710.89	1.24–9.03	132.43–964.20	(Dotun et al., 2018)
Wood dust (Gmelina)	Expanded Polystyrene (-)	0.7–1.09	< 2.3	750	–	-	(Akinyemi et al., 2019)

UF = urea–formaldehyde; MUF = melamine urea–formaldehyde; RLDPE = recycled low-density polyethylene.
PET = recycled polyethylene terephthalate.

3.4.2. Impact test results

The result of the impact test showed a moderate decrease with the addition of cowpea husk. A similar decrease in deformational energy absorption ability has been reported by (Gozdecki et al., 2015; Iulianelli et al., 2010). The result suggests that the filler made the composite less ductile to absorb lower impact energy. It can also be attributed to possible interfacial defects, leading to poor stress transfer between wood, CPH and the polymer matrix. At similar loading of 100%, 100% WC and 100% CPH have almost the same values of 0.141 J/mm and 0.143 J/mm, respectively.

3.5. Statistical and optimization results

Table 5 shows the values of the calculated grey relational generation, grey relational coefficient (GRC) and grey relational grade (GRG), while the resulting factor effects of the process parameters are shown in Fig. 5. The main effect plots obtained using the values in Table 5 are shown in Fig. 5, depicting that the composite with the optimal conditions is WC80, which represents 80% woodchips and 20% cowpea husk having 9.41%, 15.28% and 1137 kg/m^3 of water absorption, thickness swelling and density, respectively. Additionally, with mechanical properties of 0.127 J/mm impact, 17.96 MPa MOR and 741.56 MPa MOE. It can be inferred from the GRA optimization that 20% wood replacement gives better properties than boards made with 100% wood. Table 6 shows the optimal result obtained in comparison with other agro-based PBD from literature..

4. Conclusions

The feasibility of using cowpea husk in the production of wood based composite board with recycled polypropylene (rPP) as binder was studied. The boards produced are dimensionally stable, as they possess a small range between 3.98% and 24.02% for water absorption and 8.7% and 16.81% for thickness swelling. The densities obtained met the standard requirement of JIS.A.5908, with minimum and maximum values of 1047 kg/m^3 and 1137 kg/m^3, respectively. Addition of cowpea husk increased the impact strength of composites from 0.121 to 0.143 J/mm. The flexural strength (MOR) and flexural modulus (MOE) gave lower values between 6.17 and 17.96 MPa for MOR, 290.19 to 904.63 MPa for MOE. Physical and mechanical properties of the samples produced are comparable to other agro residue wood based composite in the literature. Grey relational analysis showed that the optimum composite is a mixture of 80% woodchips and 20% cowpea husk, with 9.41% water absorption, 15.28% thickness swelling, 1137 kg/m^3 density, 0.127 J/mm impact and an MOR of 17.96 MPa and 741.56 MPa. The results obtained suggests that it is technically viable to produce particleboard with partial or total replacement of woodchips with cowpea husk. Using cowpea husk and recycled polypropylene in board manufacturing will contribute to the solution of raw material shortage for the board industry and alleviate environmental problems caused by waste plastics. Additionally, it will reduce pressure on other forest resources and create job opportunities. Further studies need to be conducted on the effect of recycled polypropylene proportion on the physical and mechanical properties of the composites and to understand the mechanisms that led to altered property profiles in the boards.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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