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Multi-Criteria Performance Evaluation and Optimization of Composite Particleboard Materials: A Grey Relational Analysis Approach

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ABSTRACT

This study presents a comprehensive multi-criteria decision analysis (MCDA) of fifteen composite particleboard materials based on their fundamental physical and mechanical properties. The evaluation utilized Grey Relational Analysis (GRA) to systematically rank particleboard compositions according to five critical performance parameters: density (D), water absorption (WA), thickness swelling (TS), modulus of rupture (MOR), and modulus of elasticity (MOE). The Grey Relational Grade (GRG) methodology revealed significant performance variations among different particleboard compositions. The analysis identified sawdust waste reinforced with plastic-based resin (waste styrofoam) as the optimal composition, achieving the highest GRG value of 0.8143 (81.43%), indicating superior overall performance characteristics. Conversely, cement-bonded particleboard manufactured from pine (Pinus caribaea M.) sawdust and coconut husk/coir (Cocos nucifera L.) demonstrated the lowest performance with a GRG value of 0.4279 (42.79%). The research methodology employed systematic normalization procedures and grey relational coefficient calculations to establish comprehensive performance rankings. Results indicate that material composition and binder selection significantly influence particleboard performance characteristics, with plastic-based resins demonstrating superior mechanical properties compared to traditional formaldehyde-based binders. This investigation provides a quantitative framework for optimizing composite particleboard manufacturing processes and material selection strategies. The findings contribute to sustainable materials engineering by identifying high-performance alternatives utilizing waste materials, thereby supporting circular economy principles in the wood products industry. The established ranking system serves as a decision-support tool for manufacturers seeking to optimize particleboard compositions for specific applications while maintaining cost-effectiveness and environmental sustainability.

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1. Introduction

This research study examined, categorized, and evaluated various particleboard composites according to their physical and mechanical characteristics utilizing Grey Relational Grade (GRG) methodology. Rising wood demand has driven up timber prices, consequently spurring enhanced research and development of alternative raw materials that can partially or completely substitute wood in particleboard manufacturing (Sallehuddin *et al.*, 2008). Recovering wood waste from timber processing operations and end-of-life wood products is essential from both environmental and economic perspectives, as these materials serve as valuable raw materials for particleboard manufacturing (Olorunnisola & Adefisan, 2002). To address the rapid depletion of wood

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resources and establish alternatives to conventional wood products in timber and related industries—while supporting global Sustainable Development Goals (SDGs)—the utilization of renewable resources and their by-products/waste materials requires thorough investigation and research for developing particleboards with varying compositions. This approach will foster increased development and manufacturing of particleboards from recycled wood and agricultural waste materials.

Raw materials employed in particleboard production encompass, but are not restricted to: solid wood residues, agricultural waste materials including rice husks, coconut husks/fibers, sugarcane bagasse, corn cobs, cassava stems, municipal solid waste, and similar materials. Particleboard quality is assessed through its physical and mechanical characteristics, including board density, thickness swelling, tensile strength, surface hardness, abrasion resistance, modulus of rupture, and modulus of elasticity. The physical and mechanical characteristics of particleboard significantly influence its effective utilization and determine its application scope, whether for residential or industrial purposes. These properties are influenced by the raw material composition used in particleboard manufacturing and can be enhanced to improve the functionality, quality, and broader application potential of particleboard products (Muruganandam *et al*., 2016).

Recently, there has been substantial growth and progress in utilizing wood-based composite materials as primary replacements for solid wood consumption (Mohanty *et al*., 2015). Global demand for various composite wood products—including hardboard, medium-density fiberboard, oriented strand board, veneer board, plywood, and particleboard—continues to expand (Chen *et al*., 2006). Indeed, particleboard demand remains exceptionally high due to infrastructure development, interior design applications, furniture production, flooring systems, office construction, educational facility development, and various industrial requirements. Consequently, this substantial particleboard demand has placed pressure on limited natural resources, potentially compromising their future availability. Therefore, developing dependence on alternative natural raw materials for particleboard production becomes crucial. Agricultural residues and non-wood plant fibers present viable alternatives to satisfy particleboard requirements (Wang & Sun, 2002; Lykidis & Grigoriou, 2008).

The many desirable properties of particleboards include, but are not limited to: high board density, water resistance, high durability, abrasion resistance, high surface hardness, tensile strength *etc*. Improved physical and mechanical properties can be obtained by the impact of the board density and the particle size. The differences in the board types will result in differences in the physical and mechanical properties of the composite particleboards (CPB's). The increase in the press time during manufacturing will also necessitate an improvement in the physical and mechanical properties of the CPB's (Ghalehno *et al*., 2013). Various board densities and various kinds and combinations of wood species, raw materials forms and manufacturing methods have made the relationship between board properties and manufacturing variables complex (McNatt, 1980). The main factor responsible for the improvement in the properties of CPB's is the uniform distribution of the particles and the binders in the microstructure of the board composites (Suleiman *et al*., 2013). Particleboards are manufactured in various shapes, sizes, densities and thickness. Particleboard applications can be in furniture, tabletops, cabinetry, cupboards, wall and floor panels, laminating doors, shelves, and non-structural applications *etc*.

In this investigative research, the physical and mechanical properties of particleboards manufactured from different raw materials and combinations are surveyed and graded using Grey Relational Grade (GRG). The physical and mechanical properties of particleboards are dependent on the kind of raw material used for the production as investigation and study has proven. The particleboard properties play the major role after the manufacturing as per comparison with standards.

The multi-criteria decision analysis (MCDA) was done using Grey Relational Analysis (GRA). The Grey Relational Analysis was used to obtain the Grey Relational Grades (GRG's) of both the physical and mechanical properties of the particleboard materials obtained from the experiments. Grey Relational Analysis (GRA) is a multi-variable time series data (MTS) analytical approach. It serves as an alternative to the conventional statistical problems. Grey Relational Analysis (GRA) is used to obtain the Grey Relational Grade (GRG) used to define relationships among data variables and to obtain the vital variables that significantly impact some discrete objectives (Sallehuddin *et al*., 2008).

In this investigative research, particleboards produced from different composites and binders (or resins) were assessed based on their physical and mechanical properties which determine their performance, durability, quality, resilience and utilization. The particleboards examined, graded and ranked in this investigative research study with their different compositions and binders were sourced from various related literatures reviewed. They include: Physical and Mechanical Properties Evaluation of Particle Board produced from Saw Dust and Plastic waste (recycled polyethylene terephthalate) (PF or PET) (Atoyebi *et al*., 2018); Artificial neural network evaluation of cement-bonded particle board produced from red iron wood (Lophira alata) sawdust and palm kernel shell residues (Atoyebi *et al*., 2018); Selected physico-mechanical properties of cement-bonded particleboard made from pine (Pinus caribaea M.) sawdust-coir (Cocos nucifera L.) mixture (Erakhrumen *et al*., 2008); Trial Production and Testing of cement-bonded particles board from rattan furniture waste (Olorunnisola & Adefisan, 2002); Physical and Mechanical Properties of Bamboo (Bambusa Vulgaris Schrad. Ex Wenld) Based Cement - Bonded Composites As Influenced By Production Variables (Falemara *et al*., 2016); Effects of board density and mixing ratio on the physico-mechanical properties of cement-bonded particle board produced from Ceiba pentandra Sawdust (Ogunjobi *et al*., 2019); Strength and Dimensional Stability of Cement-Bonded Boards Manufactured From Mixture of Ceiba Pentandra And Gmelina Arborea Sawdust (Adelusi *et al*., 2019); Effect of wood particle geometry and pre-treatments on the strength and sorption properties of cement-bonded particle boards (Amiandamhen & Izekor, 2013); Assessment of Periwinkle Shells Ash as Composite Materials for Particle Board Production (Abdullahi & Sara, 2015); Particle boards produced from cassava stalks: Evaluation of physical and mechanical properties (Aisien *et al*., 2015); Development of Particleboard from Waste Styrofoam and Sawdust (Abdulkareem *et al*., 2017); Suitability of Mango Seed Shell Particles and Recycled High Density Polyethylene (RHDPE) Composites for Production of Particleboard (Abolaji *et al*., 2017); Some properties of composite corn-cob and sawdust particle boards using Urea Formaldehyde as a Binder (Akinyemi *et al*., 2016); Evaluation of Particleboard from Sugarcane Bagasse and Corn-Cob using Urea Formaldehyde as a Binder (Atoyebi *et al*., 2019); and finally, Development of coconut coir-based lightweight cement board (Asasutjarit *et al*., 2007). This investigative research study focuses on the study of the above fifteen listed different processes of particleboards and their grading and ranking using the Grey Relational Grade (GRG) to determine the particleboard processes with the best/optimal physical and mechanical properties in descending order for diverse applications, *e.g*. domestic, industrial and commercial utilizations *etc*.

2. Materials and Methods

The review of related literature was centered on the study of diverse composites of particleboards and their consequent physical and mechanical properties for suitability in diverse applications. The scholars and their associated selected composite particleboards (CPB's) for grading and ranking by GRG method in this investigative research study, and the methods of production of the composite particleboards (CPB's) selected are presented below: Atoyebi *et al*., 2018, in the "Physical and Mechanical Properties Evaluation of Particleboard produced from Saw Dust and Plastic Waste (recycled polyethylene terephthalate) (PF or PET)" used flat-pressed method to investigate a composite matrix from sawdust (SD) and recycled polyethylene (PET) at various weight ratios. Materials used in this investigation are sawdust, plastic waste [polyethylene terephthalate (PF or PET) bottles], and top bond (urea formaldehyde resin) as binder. Mechanical properties [modulus of elasticity (MOE) and modulus of rupture (MOR)], and physical properties [density, water absorption (WA), and thickness swelling (TS)], were derived based on the ratios of mixing in agreement to the standard. After 2 hours and 24 hours of immersion in the water, WA and TS were measured. Atoyebi *et al*., 2018, also evaluated the "Artificial neural network evaluation of cement-bonded particle board produced from red iron wood (Lophira alata) sawdust and palm kernel shell residues." The particleboard was manufactured as a result of a synergistic combination of effective factors; percentage compositions of cement, sawdust and palm kernel shell varied between 25-40, 20-50 and 20-50 respectively. Erakhrumen *et al*., 2008, in the "Selected Physico-Mechanical Properties of Cement-Bonded Particleboard made from Pine (Pinus Caribaea M.) Sawdust - Coir (Cocos Nucifera L.) mixture, a by-product from processed agricultural crop at different mixing ratios." The particleboard formation configurations are: (i) Sawdust: Coir ratio = 100:0; 90:10; 80:20; 70:30; 60:40 (weight: weight) (ii) Cement: Sawdust-Coir ratio = 2:1; 2:2 (weight: weight) (iii). Additive concentration ($CaCl_2$) = 3.0% (based on the weight of the cement). In the Trial Production and Testing of Cement-Bonded Particleboard from Rattan Furniture Waste by Olorunnisola & Adefisan, 2002, the commercial Portland cement was used as a binder for the study. An additive, $CaCl_2$, was used to improve the miscibility of cane furnish with cement. $CaCl_2$ was adopted based on its ability as an effective and economical accelerator for cement hydration and has been commonly employed by the cement-wood board producers. Cement-cane mixing ratios (based on weight of cement and oven-dry weight of cane particles): 2.5:1.0; 2.75:1.0; 3.0:1.0; 3.25:1.0 were used. Additive concentration levels are: 2.5%; 3.0%; 3.5%. In the "Physical and Mechanical Properties of Bamboo (Bambusa Vulgaris Schrad. Ex Wenld) Based Cement - Bonded Composites as Influenced By Production Variables by Falemara *et al*., 2016, the mixture of Bambusa vulgaris (Bamboo) particles and inorganic binder (Cement) was used to manufacture the cement-bonded composites, with $CaCl_2$ acting as the chemical additive. The value of the optimal density is 1200kg/m³. Ogunjobi *et al*., 2019, in the "Effects of Board Density and Mixing Ratio on the Physico-Mechanical Properties of Cement-Bonded Particle Board Produced from Ceiba Pentandra Sawdust" studied the physical and mechanical properties of cement bonded particleboards produced from the sawdust of C. Pentandra.

The variables of production examined were two board densities (1300kg/m³ and 1200kg/m³) and three different sawdust to cement mixing ratios; 1:2, 1:2.5 and 1:3. Adelusi *et al*., 2019, in the "Strength and Dimensional Stability of Cement-Bonded Boards Manufactured from Mixture of Ceiba Pentandra and Gmelina Arborea Sawdust" examined the influence of weight to weight proportion of C. Pentandra and G. Arborea blended at levels of 100:0, 75:25, 50:50, 25:75 and 0:100 in mass and mixing ratios of cement to wood 2:1 and 3:1 on MOR, MOE WA and TS properties of the experimental boards for 24 h and 48 h immersion in cold water. Amiandamhen & Izekor, 2013, in the "Effect of wood particle geometry and pre-treatments on the strength and sorption properties of cement-bonded particle boards" investigated wood particles (flakes) and sawdust particles of Gmelina arborea mixed with cement and water in the production of composite boards. The hot-water treatment, calcium chloride ($CaCl_2$) treatment and a combination of hot water and $CaCl_2$ treatment and a control was used to pre-treat the wood particles. A cement-wood ratio of 3:1 by weight was used for this study, resulting in a board density of 1200kg/m³. Abdullahi & Sara, 2015, in his work, "Assessment of Periwinkle Shells Ash as Composite Materials for Particle Board Production under variations of the filler weight (5, 10, 15 and 20) % wt. using compression moulding method." Aisien *et al*., 2015, in "Particle boards produced from cassava stalks: Evaluation of physical and mechanical properties" investigated cassava stalks particleboard using urea-formaldehyde as a binder. The probable use of cassava stalks for the production of bonded particle boards. Particle boards were manufactured from cassava stalks using urea-formaldehyde as a binder. Tests were carried out on WA and TS to determine dimensional stability of the boards while MOR and MOE tests were carried out to evaluate the mechanical strength of the boards. Abdulkareem *et al*., 2017, in the "Development of Particleboard from Waste Styrofoam and Sawdust" used plastic based resin (PBR) synthesized from waste Styrofoam as binder in the production of particleboard. Three particleboard panels namely C1 (20% PBR + 80% sawdust fibers), C2 (30% PBR + 70% sawdust fibers) and C3 (40% PBR + 60% sawdust fibers) were prepared respectively. Abolaji *et al*., 2017, in the "Suitability of Mango Seed Shell Particles and Recycled High Density Polyethylene (RHDPE) Composites for Production of Particleboard" produced mango shell composite boards by compressive moulding using recycled high density polyethylene (RHDPE) as binder. The RHDPE was varied between 30 to 70 % wt. at intervals of 10% wt. using 420µm particle size. Akinyemi *et al*., 2016, in "Some Properties of Composite Corn-Cob and Sawdust Particleboards" researched on the possibility of developing a composite corn-cob (CC) and sawdust (SD) particleboard using urea formaldehyde as binder. The panels were made using 0%, 25%, 50%, 75% and 100% variations for both agricultural wastes with a constant volume of adhesive to assess their impact on the physical and mechanical properties. In the "Evaluation of Particleboard from Sugarcane Bagasse and Corn-Cob", Atoyebi *et al*., 2019, evaluated particleboard made using corn-cob (CC) particles and mixing it evenly in varying percentages of 20%, 40%, 50%, 60% and 80% with sugarcane bagasse (SB) using urea formaldehyde resin as adhesive. In the "Development of coconut coir-based lightweight cement board", Asasutjarit *et al*., 2007, examined a mixture ratio of coconut coir (fiber), cement and water. Three mixing ratios by weight were varied 1:2:1, 1:1:1 and 2:1:2 respectively (cement: coconut coir: water).

Conventionally, particleboards are produced from specific particles adhered together with a thermosetting resin. Such resins are mostly formaldehyde based, which are usually synthesized from petrochemical raw materials. When heat and pressure are used to reinforce small refined particles of various raw materials impregnated with resins, or other appropriate binders particleboard is produced. The materials of the particleboard and the manufacturing process of the particleboard had been the major difference between particleboards and other conventional wooden boards. Particleboards are employed both in domestic, commercial and industrial applications as partition walls, windows and entrance doors, table tops, board sheets etc. Grinder, material handling equipment, shredder, dryer, sieve shaker, resin impregnation unit, hydraulic presser with heating apparatus, etc., are some of the vital equipment required for particleboard production.

Particleboards are generally manufactured through the following step-by-step flow process indicated below:

Collection of raw material → Drying → Segregation of waste → Shredding and Grinding of the Waste → Impregnation with Resin → Moulding and Pressing using Hydraulic Press → Particleboard Drying → Trimming, Finishing and Laminating → Particleboard.

2.1 Physical and Mechanical Properties

The right environment where a particleboard serves a purpose and where the particleboard will be considered to be utilized would be guaranteed by the all vital statistics on the physical and mechanical properties of the composite material which would be satisfied by the data. For the comprehensive analysis of the physical and mechanical properties of composite particleboard (CPB) manufactured from various kinds of materials, data on the impact of thickness swelling, density, moisture content, water absorption, internal bonding strength, compressive strength, flexural strength, tensile strength, rate of loading, press temperature, press time and hardness are very much crucial and required. Table 1 displays different composite particleboards and their grading and ranking based on their physical and mechanical properties which influences their utilization and application. The type of materials and resin used in the manufacture of any CPB will also determine the data on the physical and mechanical properties. As the application of engineering methods on almost all materials is practically possible provided enough data on the strength and the elastic properties of that material as well as its behavior under load is available, such is applicable to composite particleboards. Many physical and mechanical properties of CPB's are considered in assessing the quality of composite particleboards, but some of the basic properties selected in this survey/investigative research and are common among all the previous literatures reviewed and considered are:

(a) Density

It is noteworthy that the particleboard density is impacted by the variance in the raw material and impregnation ratio. All particleboards of commercial standard should be medium-density particleboards between 37-50 lb/cubic ft. Board density impacts heavily on properties like MOR, MOE, IB, TS and WA *etc*.

Density (g/cm^3) = W_a/V_a (a)

W_a- air dried weight

V_a – air dried volume

(b) Water Absorption

Water absorption is determined by cutting a test piece of the CPB and immersing in distilled water in a glass vessel at room temperature 20 - 30^0 for a certain period of time (2 hours, 24 hours *etc*.) until constant weight was observed. The impact of water absorption on properties such as bending stiffness and bending strength is very fatal. Strength properties of a particleboard could be decreased because of water. Therefore, water absorption property of a particleboard is very crucial for any type of particleboard.

Water absorption (%) = $(W_f – W_i/W_i)*100$ (b)

W_f – final weight

W_i – initial weight

(c) Thickness Swelling

The impact of thickness swelling is due to moisture and water absorption properties of the CPB. Thickness swelling should not exceed 2-3%. Thickness swelling becomes very much low after drying. The CPB sample is immersed in distilled water at room temperature for thickness swelling test.

Thickness swelling (%) = $(T_f - T_i/T_i)*100$ (c)

T_i = initial thickness

T_f = final thicknes

(d) Bending Strength or Modulus of Rupture (MOR)

What determines the usage and application of the CPB as a structural material is the modulus of rupture (MOR). The board density would determine the property results. A concentrated load would be applied at the center with a length of fifteen times the thickness of the sample. MOR is calculated by the load deflection curves using the formula:

MOR= $3P_bL/2bh^2$ (d)

Where P_b – Maximum load
L – Span length in mm
b – Width of the specimen in mm
h – Thickness of the specimen in mm

(e) Bending Stiffness or Modulus of Elasticity (MOE)
The stiffness or resistance to bending when load is applied is measured by the all-important property of particleboard called modulus of elasticity (MOE).

MOE = $P_{bp}L^3/4bh^3Y_p$ (e)

Where P_{bp} – load at the proportionality limit
L – Span length in mm
b – Width of the specimen in mm
h – Thickness of the specimen in mm
Y_p – deflection corresponding to P_{bp} (mm)

The modulus of rupture (MOR) and modulus of elasticity both indicate the impact due to moisture content, particle size and the type of raw material used in the particleboard production. The Multi Criteria Decision Analysis (MCDA) was done using Grey Relational Analysis (GRA). The Grey Relational Analysis was used to obtain the Grey Relational Grades (GRG's) of both the physical and mechanical properties of the particleboard materials obtained from the experiments. The following equations were used in the Grey Relational Analysis (GRA) for the Multi Criteria Decision Analysis (MCDA) of the physical and mechanical properties of the of the surveyed/ investigated particleboard composite materials. If the attribute of a response is the larger the better characteristics, the normalized value is given by:

$$X_i(k) = \left(\frac{x_i(k) - x_{min}(k)}{x_{max}(k) - x_{min}(k)}\right) \quad (1)$$

Here $x_i(k)$ is the response of the i^{th} experiment for response characteristics k.

For smaller the better characteristic, the normalized value is given by:

$$X_i(k) = \left(\frac{x_{max}(k) - x_i(k)}{x_{max}(k) - x_{min}(k)}\right) \quad (2)$$

The Grey Relational Coefficient (GRC) is given by:

$$\gamma_i(k) = \left\{\frac{\varepsilon\delta_i(max) + \delta_i(min)}{\varepsilon\delta_i(max) + \delta_i}\right\} \quad (3)$$

Here δ_i is given by:

$$\delta_i = (X_i)_{max}(k) - X_i(k) \quad (4)$$

k is the response characteristics under consideration.
ε is the dynamic distinguishing coefficient and its values are: $0 \leq \varepsilon \leq 1$.
In this study the value of 0.5 was used for ε.

The Grey Relational Grade (GRG) is given by:

$$\tau_i = \frac{1}{n}\sum_{k=1}^{n}\gamma_i(k) \qquad (5)$$

Here τ_i refers to the GRG of the i^{th} experiment and n is the number of characteristics. able 1 shows the ranking of the particle board materials based on the GRG obtained from the mathematical model described in Equations 1 to 5. From Table 1 particle board material derived from Sawdust Wastes and Plastic Based Resin (PBR) (Waste Styrofoam) had the best properties, while Cement-Bonded Particleboard made from Pine (Pinus Caribaea M.) Sawdust and Coconut Husk or Coir (Cocos Nucifera L.) had the worst properties. The modulus of rupture value of 380.81 N/mm^2 obtained for particle board material derived from Sawdust Wastes and Plastic Based Resin (PBR) (Waste Styrofoam) was actually very high (an outlier) compared to other competing materials, and must have influenced its grade to become the best particleboard material from the survey. Therefore, it is suggested that this result be subjected to further investigation for a possible outlier.

3. Results

The results of this survey/investigative research are analyzed and tabulated below. Table 1 displays different composite particleboards and their grading and ranking based on their physical and mechanical properties using GRG, which would influence their resultant utilization and application areas. The GRG grading and ranking showed the particleboard made from Sawdust Wastes (SW) and Plastic-Based Resin (PBR) [Waste Styrofoam] having the best GRG result with a value of 0.8143 (81.43%) GRG, and was ranked number one (1st) according to the GRG ranking, depicting the particleboard composition with the best physical and mechanical properties among all the CPB's under consideration. From the GRG results, Cement-Bonded particleboard made from Pine (Pinus Caribaea M.) Sawdust and Coconut Husk/Coir (Cocos Nucifera L.) showed the least GRG with a value of 0.4279 (42.79%) GRG, and was ranked the least, number fifteen (15th), depicting the particleboard composition with the least/poorest physical and mechanical properties. The CPB that lies at the middle of the grading and ranking is the Periwinkle Shell Ash Reinforced Polyethylene Composite Particleboard with a GRG grading of 0.5130 (51.30%) and ranked 8th in position among the graded composites.

Table 1. Composite particleboard (CPB's) physical and mechanical properties with their grading and ranking based on the Grey Relational Grading (GRG)

S/N	Name	Density (Kg/m^3)	Water Absorption (WA)	Thickness Swelling (TS)	Modulus of Rupture (MOR) (N/mm)	Modulus of Elasticity (MOE) (N/mm^2)	GRG	RANK
1	Sawdust (SD) and Plastic Waste [Recycled Polyethylene Terephthal	710.8903	63.6233	5.4851	9.0390	964.1990	0.4461	14

	ate (PET) PF]							
2	Cement-Bonded Particleboard produced from Red Iron Wood (Lophira Alata) Sawdust & Palm Kernel Shell (PKS) Residues	1639.2000	1.4200	1.4100	8.8610	373.2600	0.5643	6
3	Cement-Bonded Particleboard made from Pine (Pinus Caribaea. M) Sawdust and Coconut Husk or Coir (Cocos Nucifera L.)	1350.0000	32.2000	4.0000	8.0300	130.6300	0.4279	15
4	Cement-Bonded Particleboard from Rattan Furniture Waste	1050.0000	44.7000	2.8000	1.0000	3563.0000	0.4993	10
5	Bamboo (Bambusa Vulgaris Schrad. Ex. Wenld) Based Cement-Bonded Particleboard	1200.0000	5.7400	0.2000	6.1440	2900.0000	0.6349	3
6	Cement-Bonded Particleboard produced from Ceiba	1300.0000	7.6400	2.3600	4.3200	1262.0300	0.5337	7

	Pentandra Sawdust							
7	Cement-Bonded Boards manufactured from mixture of Ceiba Pentandra and Gmelina Arborea Sawdust	1200.0000	14.8000	0.5300	3.0200	5294.3000	0.67399	2
8	Cement-Bonded Particleboards from Flakes and Sawdust Particles of Gmelina Arborea	1200.0000	3.6300	0.6900	6.9000	1897.3600	0.6113	4
9	Periwinkle Shell Ash Reinforced Polyethylene Composite (Particleboard)	460.0000	27.0000	10.0000	25.8000	98.8100	0.5130	8
10	Cassava Stalks Particleboard using Urea-formaldehyde as a binder	1000.0000	20.0000	6.2600	4.0000	2367.0000	0.4798	12
11	Sawdust Wastes and Plastic-Based Resin (PBR) (Waste Styrofoam)	487.5000	4.6000	1.0800	380.8100	675.4800	0.8143	1
12	Mango Seed Shell Particles (MSP) and Recycled High	960.0000	18.5000	4.2000	11.4900	2450.0000	0.5105	9

	Density Polyethylene (RHDPE) Particleboard.							
13	Corn-Cob (CC) and Sawdust (SD) Particleboard using Urea-formaldehyde as a Binder	459.0000	57.0900	5.8500	1.2300	71.4440	0.4983	11
14	Particleboard from Sugarcane Bagasse (SB) and Corn-Cob (CC) using Urea-formaldehyde (Top Bond) as Resin	503.0000	45.0000	9.1800	3.7000	26.3300	0.4737	13
15	Coconut Coir-Cement Particleboard	1220.0000	19.6500	3.6400	20.3400	5419.3300	0.6000	5

4. Discussion

For the CPB that came first (1st) position in the GRG grading and ranking, the sawdust wastes (SW) and plastic-based resin (PBR) (Waste Styrofoam); the panel made of higher resin content (40% PBR + 60% sawdust fibers) had stronger dimensional stability properties. The CPB with (30% PBR + 70% sawdust fibers) and above satisfied the minimum requirement of MOE and MOR for general purpose boards for use in dry conditions by ANSI A208. (30% PBR + 70% sawdust fibers) particleboards generally displayed better tensile strength than the (20% PBR + 80% sawdust fibers) particleboards attributable to the strong binding force and compaction strength at the resin – sawdust interface. PBR particleboards show more ability to resist water penetration than the urea formaldehyde particleboards. Therefore, PBR particleboards have more dimensional stability than the urea formaldehyde particleboards of comparable density. Consequently, PBR particleboards prove better application in moist or humid environment than urea or formaldehyde particleboard. PBR gave better mechanical properties to the particleboards. As a result, the PBR particleboard will exhibit better resistance to deformation than the urea or formaldehyde particleboards. Hence, the PBR particleboards will prove more durability, toughness and also show more ability to resist abrasion. PBR from Styrofoam waste is proved as a good replacement for urea or formaldehyde based resin presently used industrially.

For the CPB that came second (2nd) in the GRG grading and ranking, the cement-bonded boards manufactured from mixture of Ceiba Pentandra and Gmelina Arborea Sawdust; the optimal values were reached at cement to wood ratio of 3:1 and blending proportion of C. Pentandra : G. Arborea of 0:100. The result indicated that increasing the blending proportion of G. arborea: C. pentandra and the cement: wood mixing ratio caused decrease in WA and TS properties. The lowest values were obtained from the boards produced at 0:100 (C. pentandra: G. arborea sawdust) and 3:1 cement: wood ratio. Consequently, boards more dimensionally stable were achieved at this level as it showed relatively better performance of WA and TS of the manufactured boards. The results also indicate that MOR and MOE depend on blending proportion (BP) and cement: wood mixing ratio as they were directly impacted by each level of combination. As the contents of G. arborea increases in blending proportion related to C. pentandra sawdust and for higher cement to wood contents (mixing ratio), there was increase in MOR and MOE values. The impact of blending proportion (BP) becomes increasingly significant as the ratio of G. arborea and those of the cement content increased.

For the CPB that came third (3rd) in the GRG grading and ranking, the bamboo (Bambusa Vulgaris Schrad. Ex. Wenld) based cement-bonded particleboard; as the board density (BD) increased the WA and TS properties decreased. Thus, the production of stable, strong and stiff particleboards for better performance is enhanced by the increase in the weight of boards. As the board density (BD) increased, the MOR, MOE and the energy at break also increased. The investigation revealed that as the board density (BD) increased, the dimensional movement decreased and the strength of the boards increased. At the highest board density (BD) of 1200kg/m³, the strongest, stiffest and the most dimensionally stable boards were produced. Bamboo particles as a raw material in cement-bonded particleboard obtained from Bambusa vulgaris culms potentially and effectively utilized could serve as an alternative to wood-based products and sawn timbers used in construction works and furniture. From the findings of this study, it can be deduced that bamboo culms have potential as a fibrous supplement raw material for composites manufacturing.

For the CPB that came fourth (4th) in the GRG grading and ranking, the cement-bonded particleboards from flakes and sawdust particles of Gmelina Arborea; from the results, boards treated with both hot water and $CaCl_2$ have the least WA rate. The boards treated with hot water and $CaCl_2$ are more dimensionally stable. This finding is in agreement with earlier studies that $CaCl_2$, $MgCl_2$ and hot water are effective methods of decreasing thickness swelling. From observations, flakes particleboard composites have greater MOR values than sawdust composites. The best effect in the MOR of the flakes boards were produced by the combination of the hot water and $CaCl_2$ treatment. It was also observed that hot water and $CaCl_2$ combined treatment produced the best effect in MOE of the particleboard geometries. From the study it was observed that the cement-bonded particleboards produced from flakes displayed the best effects in strength and water absorption properties. The highest strength properties and dimensional stability was produced by the combined pre-treatment of hot water and $CaCl_2$ in the production of the particleboard composites. Hence, the consequential properties of cement-flakes bonded particleboard composites pre-treated with the combination of hot water and $CaCl_2$ could be used as a structural index for material with an adequate tolerance of moisture.

For the CPB that came fifth (5th) in the GRG grading and ranking, the coconut coir-cement particleboard; the study showed that the optimum mixture ratio is 2:1:2 (cement: coconut coir: water). When compared with commercial board composite, it is established that coconut coir-based lightweight composite have low thermal conductivity. This should be of extreme interest in regards to energy saving for use as ceiling and wall materials.

For the CPB that came sixth (6th) in the GRG grading and ranking, cement-bonded particleboard produced from Red Iron Wood (Lophira Alata) sawdust & palm kernel shell

(PKS); from the ANN analyses used for the experimental analysis, the relative importance of input factors showed that the contributive quantity made by each of the independent factors (input) to the manufacturing process as observed indicated that the change in % of sawdust has the most significant contribution to change the output followed by cement, then PKS. At the end of the experimental investigation, the following conclusions (results) were deduced: (1) Minimum water absorption (WA) can be attained with percentage composition of PKS in the range of 26% to 32%. (2) Minimum thickness swelling (TS) can be attained with percentage composition of cement in the range of 29% to 35%. (3) As cement content in the board increased, density, MOE and MOR increased. (4) The variable that has the most significant effect on the particleboard properties is sawdust followed by cement, then PKS.

For the CPB that came seventh (7th) in the GRG grading and ranking, cement-bonded particleboard produced from Ceiba Pentandra Sawdust; from the results obtained, 1300kg/m³ board density and 1:3 sawdust to cement mixing ratio yielded the best board for mechanical properties and dimensional stability and can be used for several structural applications. However, the higher the board density and the sawdust to cement mixing ratio, the lower the WA and TS of the board, and vice versa. The highest average MOR and MOE was achieved at the highest board density (1300kg/m³) and mixing ratio (1:3).

For the CPB that came eighth (8th) in the GRG grading and ranking, periwinkle shell ash reinforced polyethylene composite particleboard; from observations, there was an improvement in the mechanical properties of the polyethylene composites up to 10%wt periwinkle shell loading. The physical properties of the composite such as density increased as the loading of the periwinkle shell particles increased. Along the loading, the water absorption as well as the thickness swelling of the composite decreased. The optimum result was obtained at the periwinkle shell particulate fiber loading in the range 5 - 10%wt which shows that low fiber weight content is good for better improvement of properties.

For the CPB that came ninth (9th) in the GRG grading and ranking, mango seed shell particles (MSP) and recycled high density polyethylene (RHDPE) particleboard; from the results, the boards made using mango seed particles (MSP)/RHDPE composite in the percentage composition of (40/60)% wt. respectively produced the best physical and mechanical properties at optimal values. As the percentage of the binder increased in the particleboard, the board density (BD) increased. As the weight percentage of the RHDPE binder decreased in the composite, the WA and TS percentage increased. As the RHDPE binder addition increased, the impact strength of the board composite increased. Correspondingly, the MOE, MOR and internal bonding (IB) meet the minimum requirements of the European standards (BS EN 312:2003). The particleboard composite will find its application in general purpose functions such as ceiling, paneling, partitioning, etc., since the properties of particleboards used in this area compared favorably with the properties of the developed boards at 50-60% wt. RHDPE binder. Therefore, mango seed shell particles can be used as a replacement for wood-based particleboards for general purpose applications with a minimal cost of production.

For the CPB that came tenth (10th) in the GRG grading and ranking, cement-bonded particleboard from Rattan furniture waste; at additive levels of 2.5% optimal values were obtained, and at cement - cane mixing ratio of 2.5:1.0. The investigative study supports the assumption that rattan furniture waste is a potential valuable raw material for the composite particleboard industry (CPB) industry. The strength (MOE and MOR) and water resistance properties of the particleboards showed potentials for use as low-stressed materials for indoor (dry) applications. Inclusive in the uses could be: structural applications demanding sound/vibration absorption and energy dissipation where low bending strength and water resistance properties are not limiting necessarily.

For the CPB that came eleventh (11th) in the GRG grading and ranking, corn-cob

(CC) and sawdust (SD) particleboard using urea-formaldehyde (UF); for physical properties, the CPB with the composition of SD: CC in the ratio of 50: 50 gave the best performance. From the result obtained, none of the panels made had values of MOE and MOR that met the minimum requirement. Therefore, this suggests that the panels cannot serve for structural or load bearing purposes because they show poor mechanical properties which will be enhanced as the composition of CC increased. Within the experimental analysis and possible limitations, the panels with 50% CC content were the best preferred since they had desirable performances for both physical and mechanical properties. Hence the particleboards made from this research study with SD: CC composition of 50: 50 ratios can serve as ceiling boards and wall claddings.

For the CPB that came twelfth (12th) in the GRG grading and ranking, cassava stalks particleboard using Urea-formaldehyde (UF) as a binder; particleboards manufactured using an adhesive-cassava stalk ratio of 3:1 (75:25)% gave the best / optimal results in terms of the lowest mean values of WA and TS, as well as the highest values of MOR and MOE. Particleboards manufactured using an adhesive–cassava stalk ratio of 3:1 are more dimensionally stable. Particleboards manufactured using an adhesive–cassava stalk ratio of 3:1 have higher mechanical strengths.

For the CPB that came thirteenth (13th) in the GRG grading and ranking, particleboard from sugarcane bagasse (SB) and corn-cob (CC) using Urea-formaldehyde (UF); the results of the study showed that the particleboard with 50% CC and 50% SB using equal volume of adhesive had advantageous physical properties that are recommendable for indoor uses in buildings. Considering the experimental study and probable limitations, the panels with 50% CC and 50% SB are the best preferred since they had preferable performance for both physical and mechanical properties. Nevertheless, the panels cannot be used for structural purposes or load bearing purposes as they exhibit poor mechanical properties which tend to improve as the composition of CC increased from 40% to 100%.

For the CPB that came fourteenth (14th) in the GRG grading and ranking, sawdust (SD) and plastic waste (recycled polyethylene terephthalate) (PF or PET); after 2 hours of immersion in water, WA and TS produced the optimal results. From the results, as the density increased, sawdust (SD) content decreased from 90% to 50% into the matrix. But when the PET content increased in the matrix, WA and TS decreased. However, the particleboard with 50:50 ratio of SD: PF gave the optimal result of WA and TS, MOE and MOR. Notably, the MOE and MOR reached an optimal point at 964.199 N/mm² and 9.039 N/mm² respectively in the 50% SD content. At the SD: PF ratio of 50: 50 (weight: weight), the sawdust (SD) composition in (ml) is 1260, plastic fiber (PF) in (ml) is 1260, fine sizes (80% of PF) in (ml) is 1008, coarse sizes (20% of PF) in (ml) is 252, while the adhesive in (ml) is 630. From the results, the optimal density is at SD content of 50% into the matrix. Comparing with practical standard, the particleboard with the optimal values at SD and PF content of 50% respectively can be categorized as medium-density particleboards. From the results, it could be inferred that the production of wood particle composites (WPCs) from sawdust (SD) and PET would be technically possible for indoor purposes in buildings due to the advantage of physical properties displayed. But the mechanical properties exhibited indicate that it cannot serve for structural or load bearing purposes.

For the CPB that came fifteenth (15th) in the GRG grading and ranking, cement-bonded particleboard made from pine (Pinus Caribaea M.) sawdust and coconut husk or coir (Cocos Nucifera L.); the water resistance (WA), thickness swelling (TS), strength properties (MOE and MOR) and as well, the density were at their optimal levels in the particleboards with high cement content in the various mixing ratios. Particleboards of this specification can be used in bearing wall construction, flooring, partitioning, and other applications requiring relatively high strength/mechanical properties mainly where there is little or no danger of extreme moisture variations due to the dimensional stability properties obtained for the various board specifications.

5. Conclusions

Tremendous gains are to be made in using sustainable alternatives to wood-based materials for particleboard production. The similarity in their composition, manufacturing process, properties and application are significant, and they are almost the same. As such, the differences in their qualities would hardly be identified. The uniformity in the distribution of particles and binders/resins in the microstructure of the composite particleboards plays the major role in the improvement of the board properties. Particleboard strength (Modulus of Rupture, Modulus of Elasticity, Internal Bond Strength or Tensile Strength) is enhanced by various fibers. The most vital property to investigate in any type of composite particleboard is the water absorption/resistance (WA) and the thickness swelling (TS) to make a comparison with the conventional particle boards. The ratio of the particle to the binder is also critical to take into consideration as both the physical and mechanical properties of CPBs depend much on this ratio. The binder/resin ratio has significant impact on the resultant physical and mechanical properties of CPBs. The GRG grading and ranking used in this investigative/survey research has generated a grading and ranking of CPBs, and the results would be useful and serve as a reference framework for the end-users engaged in the manufacture of composite particleboards. The various material compositions of the graded and ranked composite particleboards should also be adopted and employed in practical use and in the manufacture of the associated composite particleboards (CPBs).

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