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NUMERICALLY OPTIMIZED EFFECT OF PHYSICAL PROPERTIES OF BONDED PARTICLE BOARDS PRODUCED FROM WASTE SAWDUST

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Abstract

This study aimed to optimize the production of particle boards from agricultural waste (sawdust). The physical properties studied were Water Absorption (WA), Thickness Swelling (TS) and Linear Expansion (LE). The production of particle boards was investigated under the following conditions: stacking time (14-21 days), resin loading (386-463 g) and amount of agro residue (154-185 g) using Box-Behnken design. Statistically significant models ($p<0.05$) were developed to represent the relationship between the responses (WA, TS and LE) and the independent factors. The three models showed significant fit with experimental data with R^2 values of 0.99, 0.99 and 0.97, respectively. Analysis of variance (ANOVA) results showed that WA, TS and LE were influenced by the stacking time, amount of resin and agro residue used. Response surface methodology (RSM) was used to optimize the WA, TS and LE, and the results showed that the minimum WA, TS and LE values of 4.05%, 0.38%, and 0.34% were respectively obtained at the optimum production conditions of stacking time, resin loading and amount of agro residue (i.e. 21days, 462.82g and 185.00 g respectively). The particle board produced at the optimized conditions satisfied the American National Standard Institute ANSI/A208.1-1999 specification for general-purpose particle boards.

Keywords: Box-Behnken, Linear expansion, Optimization, Particle board, Sawdust, Thickness swelling, Waste recycling, Water absorption.

Introduction

The growing environmental problem experienced in developing countries is due to the buildup of agricultural waste residues (Jannat et al., 2021) and reducing the amount of this waste deposited into the environment has called for great concern (Odeyemi et al., 2020). The Resource Conservation and Recovery Act (RCRA) of 1976 defined “solid waste” as any garbage or refuse from water or wastewater treatment effluent and other rejected material from commercial, industrial, and agricultural operations (USEPA 2023). Therefore, solid waste can be classified according to its source, composition, phase, treatment required etc. It includes residential, municipal, mining, agricultural, industrial and so on (Abhishek et al., 2017). Globally, waste generated from industrial, urbanization and agricultural activities has caused great negative impact on our environment (Emmanuel and Edidiong, 2020, Young et al., 2010, Jannat et al., 2021). In recent years, researchers have tried to reduce the number of agro residues by finding alternatives to waste management. Several studies have shown agro-waste can be used for the production of building material (Eyide et al., 2023, Al-Fakih et al., 2019, Laborel-Preneron et al., 2018, Jannat et al., 2020) via recycling of the agro-waste (Tomas et al., 2017) to valuable products.

Currently, the construction industry in Nigeria is experiencing a continuous increase in the price of building materials while battling with an unwavering demand for these materials (Amenaghawon et al., 2016). This increasing demand for construction materials and the challenge faced with waste management have necessitated the development of valuable materials through proper waste management (Jannat et al., 2021). According to Harshavardhan and Muruganandam (2017), scientific interest has been directed toward the wood industries due to the large amount of toxic solid waste released into our environment. One of the environmental issues linked with wood industries is the utilization of wood particles (sawdust) into valuable products. Large volumes of sawdust are produced in Nigeria in sawmills and wood-based industries, and burning them produces smoke and carbon dioxide, which are harmful to human health and contribute to the depletion of the ozone layer (Odeyemi et al., 2020). Nigeria generates about 1.8 million to 5.2 million tons of sawdust annually, with 1,000,000 m^3 generated in 2010 alone (Jacob et al., 2016). Hence, waste products from the wood industry can be converted into valuable resources within the same industry. The reuse/recycling of these wood residues in Nigeria will reduce the pressure on our ever-decreasing forests, reduce environmental pollution, and create wealth and employment (Lacovidou et al., 2017). An example of recycling is turning sawdust into valuable products such as particle boards (Harshavardhan et al., 2017; Emmanuel et al., 2020; Abdulkareem et al., 2017).

Particle boards have found significance in homes, offices, schools, and general furnishings (Wang and Sun., 2002; Wang et al., 2008; S. Fono-Tamo et al., 2014). Due to their composite in nature, they can be formed from wood particles such as sawdust, wood chips, and planar shavings, and non-wood particles such as sugarcane bagasse, corn hubs, wheat straw etc. (Eyide et al., 2023; Ikubanni et al., 2018; Odusote et al., 2016), bonded with a suitable adhesive and compressed into a single material (Melo et al., 2014). Different feedstock materials could be used along with sawdust to produce composite particleboard. Melo et al. (2014) explored the use of bamboo, rice husk and wood in producing particle boards, while other feedstocks include watermelon peels (Lias et al., 2014), wood chips (Eyide et al., 2023), peanut shells and glass powder composite (Sahin et al., 2017) and a corn cobs and cassava stalk blend by Amenaghawon et al., (2016).

A study by Odeyemi et al. (2020) showed that the Water Absorption (WA) and Thickness Swelling(TS) of particle boards are influenced by the amount of resin and sawdust. Another study by Emmanuel et al. (2020) on the production of particleboard from starch-based-modified resin and sawdust, it was revealed that the water absorption value ranged from 1.06 to 9.31 %, and thickness swelling value ranged from 4.55 to 4.78% which conforms with ANSI A208.1 (1993) standards. Similarly, a study conducted by Hassan et al. (2019) on the production of particle boards from common agro wastes in Nigeria revealed sample D with a density of 860(Kg/m^3), has a minimum value of 5.44% WA and 1.26% TS respectively, followed by sample E with the same density, which has a minimum value of WA and TS of 9.67 % and 2.28 % respectively. In the same research conducted by Hassan et al. (2019), it was also revealed that the board density of 860 Kg/m^3 for sample G and H have high water absorption and low thickness swelling. The water absorption for samples G and H is 35.96 % and 31.24 %, respectively, while their Thickness swellings are 5.91% and 12.11 %, respectively. Also, Sample F, with a board density of 840 Kg/m^3, had the highest water absorption and lowest thickness swelling of 47.97 % and 1.26 %, respectively. From the research conducted by Hassan et al. (2019), it could be concluded that the high water absorption tendency is due to high percentage of rice husk in the mixture in board while the decrease in water absorption was due to the high proportion of sawdust in the board. The lowest value of WA and TS obtained in samples D and E by Hassan et al. (2019) was in conformity with the American National Standard ANSI/A208.1-1999 and International Standard (IS3087) for particle board with good water absorption and thickness swelling, which is expected to be less than and equal to 40 % and 12% respectively.

A recent study by Eyide et al. (2023) investigated the optimization of mechanical properties of bonded particle boards produced from agricultural waste wood. The results showed that the maximum modulus of elasticity and rupture were 1114.09N/mm^2 and 9.34 N/mm^2 respectively obtained at conditions of 21 days stacking time, 462.82g resin loading and 185.00g of agro residue. This study, thus, aims to optimize the physical properties of bonded particle boards produced from agricultural waste sawdust using top bond adhesive as a binder.

Materials and Methods

Materials collection and pretreatment

The agro residues used in this study, sawdust, were obtained from a sawmill at Uselu market in Egor local Government Area, Edo state, Nigeria. Top bond adhesives used as binders were obtained from the Uselu market in the Egor Local Government Area of Edo state of Nigeria. The sawdust was properly washed and sun-dried for 2 months to remove sand and dust particles that could affect the quality of the particle board sheet. The residues were milled using a hammer mill and then screened using standard sieves to obtain 2mm particles. To ensure and enhance the proper settling of the particle board sheet, the milled residues were transferred into hot water at a constant temperature of 90 ^{o}C to extract inhibitory sugar compounds such as glucose, hemicelluloses and lignin (Sotannde et al., 2012), which was done to ensure the proper setting of the boards. The treated residue materials were separately air-dried to attain approximately 9- 12% moisture content before use.

Design of experiment

A three-variable Box-Behnken design for response surface methodology was used to study the combined effect of stacking time, resin loading and amount of agro residue on the physical properties of the particleboards produced. The range and levels of the independent variables are shown in Table 1.

Table 1: Coded and actual levels of the factors for three-factor Box-Behnken design for particle board production

Independent Variables	Symbols	Coded and Actual Levels		
		-1	0	+1
Stacking time (days)	X1	14.0	17.5	21.0
Resin loading (g)	X2	386.0	424.5	463.0
Amount of agro residue (g)	X3	154.0	154.0	185.0

The Box-Behnken design has been established to be suitable for exploring quadratic response surfaces and this design generates a second degree polynomial model that can be used for optimization purposes (Amenaghawon et al., 2013).

The number of experimental runs for this design was obtained from equation (1).

$$N = k^2 + k + c_p \qquad (1)$$

Where k is the number of factors and c_p is the number of replications at the centre point. The design for producing particleboards was developed using Design Expert® 7.0.0 (Stat-ease, Inc. Minneapolis, USA) and 17 experimental runs were obtained. The coded and actual values of the independent variables were calculated using equation (2).

$$x_i = \frac{X_i - X_o}{\Delta X_i}$$

Where x_i and X_i are the coded and actual values of the independent variable, respectively. X_o is the actual value of the independent variable at the centre point, and ΔX_i is the step change of X_i. The following generalized second-degree polynomial equation was used to estimate the response of the dependent variable (Amenaghawon et al., 2013).

$$Y_i = b_o + \sum b_i X_j + \sum b_{ij} X_i X_j + \sum b_{ii} X_i^2 + e_i \qquad (3)$$

Y_i is the dependent variable or predicted response, X_i and X_j are the independent variables, b_o is the offset term, b_i and b_{ij} are the single and interaction effect coefficients, and e_i is the error term. The Design Expert software was used for regression and graphical analysis of the experimental data. The goodness of fit of the WA, TS and LE models was evaluated by the coefficient of determination (R^2) and analysis of variance (ANOVA). The optimum values of the variables tested were obtained by numerical optimization based on the criterion of desirability (Jargalsaikhan, 2008).

Table 2: Box-Behnken experimental design for particle board production

Std	Run	Block	Factor 1 A: AGRO RESIDUE (g)	Factor 4 B:RESIN LOADING (g)	Factor 4 C: STACKING TIME (days)
13	1	Block1	169.50	424.50	17.50
15	2	Block1	169.50	424.50	17.50
10	3	Block1	169.50	463.00	14.00
16	4	Block1	169.50	424.50	17.50
9	5	Block1	169.50	386.00	14.00
11	6	Block1	169.50	463.00	21.00
7	7	Block1	154.00	463.00	21.00
1	8	Block1	154.00	424.50	17.50
5	9	Block1	154.00	424.50	14.00
6	10	Block1	185.00	386.00	14.00
8	11	Block1	185.00	424.50	21.00
12	12	Block1	169.50	386.00	21.00
2	13	Block1	185.00	463.00	17.50
17	14	Block1	169.50	386.00	17.50
14	15	Block1	169.50	424.50	17.50
3	16	Block1	154.00	424.50	17.50
4	17	Block1	185.00	424.50	17.50

Particle board production and testing

The quantity of the feedstock and adhesive to be used were measured according to the result of the design given in Table 2 by the design Expert through the use of Box Behnken Design. After pretreatment, the feedstock residue (sawdust) was thoroughly mixed with the adhesive (ratio 1:2.5) to obtain a lump-free matrix. The resulting material was then put in a mat-forming box with dimensions 0.3mx0.3mx0.006m. A manual pressing machine was used to make a pressing at 0.78 N/mm^2. The box was then put in a hydraulic press, and the boards were made using an 8-minute press closing time at a pressure of 1.23x 10^6 N/mm^2 (Mendes,2009). The mat-forming box was covered with a polythene sheet before board formation to prevent the boards from sticking to the box. About 2 cm was trimmed off the edge of each board produced using a buzz saw, and the boards were subsequently put in an acclimatization chamber at a temperature of 20 ± 2 ºC and a relative humidity of 65 ±2 % (Amenaghawon et al., 2016) for a period of 14 to 21 days for the 17 experimental boards according to their stacking time. Physical tests (thickness swelling (TS), water absorption (WA) and linear expansion) were carried out on the experimental boards according to standard methods of ASTM D1037 and DIN 52362.

Determination of Water absorption (WA.)

The particle board sheet specimens were cut into sizes of 152mm by 152mm and weighed using the weighing balance to determine the initial weight (Wi). The weighed samples were soaked in the water in a large container at 20 ºC for 24 hours (1 day). After this duration, the samples were removed and re-weighed to determine the final weight (W_f).

Finally, the water absorption WA was evaluated using the equation given below:

$$\mathrm{WA}(\%) = \left[\frac{(\mathrm{W}_f - \mathrm{W}_i)}{\mathrm{W}_i}\right] \times 100 \qquad (4)$$

W_f is the final weight after soaking for 24 h, and W_i is the initial weight.

Determination of Thickness Swelling (TS.)

The thickness of the samples was measured using veneer callipers and recorded as initial thickness (T_i). After the measurement, the samples were soaked in water for 24 hours in a large horizontal container. Immediately after the soaking duration, the samples were removed, dried with a cloth and re-measured to determine the final thickness (T_f). Finally, the Thickness Swelling TS was evaluated using the equation given below:

$$\mathrm{TS}(\%) = \left[\frac{(\mathrm{T}_f - \mathrm{T}_i)}{\mathrm{T}_i}\right] \times 100 \qquad (5)$$

T_f is the final thickness after soaking for 24 hours, and T_i is the initial thickness.

Determination of Linear Expansion (LE.)

The same procedure for thickness swelling given above was repeated for Linear Expansion LE, except that instead of measuring the thickness, the initial and final length of the samples were measured before and after soaking in water using a calliper. The Linear Expansion LE was evaluated using the equation given below:

$$\mathrm{LE}(\%) = \left[\frac{(L_f - \mathrm{L}_i)}{\mathrm{L}_i}\right] \times 100 \qquad (6)$$

Where L_f is the final length after soaking for 24 hours, and L_i is the initial length

Results and Discussion

Statistical analysis

The Box-Behnken design resulted in 17 experimental runs, as shown in Table 3. Equations (4), (5) and (6) were obtained after applying multiple regression analysis to the experimental data. These second-degree polynomial equations were used to estimate the WA, TS and LE responses, respectively.

$$Y_1=+28.47+17.89\,X_1-14.38\,X_2+3.12\,X_3-31.31\,X_1X_2+13.51\,X_1X_3-5.75\,X_2X_3-4.25\,X_1^2+9.15\,X_2^2-12.56\,X_3^2 \qquad (7)$$

$$Y_2=+0.60+0.054\,X_1-0.10\,X_2-0.022\,X_3-0.046\,X_1X_2+6.536E\text{-}003\,X_1X_3-0.029\,X_2X_3-0.029\,X_1^2-0.084\,X_2^2+0.027\,X_3^2 \qquad (8)$$

$$Y_3=+0.58+0.078\,X_1-0.045\,X_2-0.023\,X_3-0.049\,X_1X_2-0.026\,X_1X_3-0.028\,X_2X_3-0.059\,X_1^2-0.10\,X_2^2+0.017\,X_3^2 \qquad (9)$$

The values of WA, TS and LE predicted by Equations (7), (8) and (9) are given in Table 3, along with the experimental data(Actual). The significance of the fit of the equations representing WA, TS and LE was assessed by an analysis of variance (ANOVA). ANOVA results show that the WA, TS and LE models were statistically significant with p values of <0.0001, <0.0001 and 0.0042, respectively, as shown in Tables 4, 5 and 6. Both models did not show a lack of fit, as seen from their “lack of fit” p values (0.1702, 0.1627 and 0.3303, respectively). For the three models, the terms representing resin loading, stacking time and amount of agro residues were significant, indicating that they significantly influence the WA, TS and LE of the boards produced.

Table 3: Box Behnken Design Matrix for the optimization variables and response values of Water Absorption, Thickness Swelling and Linear Expansion.

Run No	Variables						Response					
	Coded levels			Actual values			WA (%)		TS (%)		LE (%)	
	X1	X2	X3	X1	X2	X3	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	0	0	0	169.50	424.5	17.5	28.50	28.47	0.60	0.60	0.60	0.58
2	0	0	0	169.5	424.5	17.5	28.50	28.47	0.60	0.60	0.60	0.58
3	0	1	-1	169.5	463.0	14.0	12.82	13.31	0.50	0.50	0.49	0.50
4	0	0	0	169.5	424.5	17.5	28.52	28.47	0.60	0.60	0.59	0.58
5	0	-1	-1	169.5	386.0	14.0	30.41	30.57	0.65	0.64	0.55	30.53
6	0	1	1	169.5	463.0	21.0	6.60	8.06	0.38	0.39	0.38	0.40
7	-1	1	1	154.0	463.0	21.0	4.58	3.71	0.36	0.35	0.36	0.33
8	-1	0	0	154.0	424.5	17.5	4.67	6.32	0.52	0.52	0.42	0.44
9	-1	0	-1	154.0	424.5	14.0	4.60	4.16	0.57	0.58	0.47	0.45
10	1	-1	-1	185.0	386.0	14.0	62.23	62.02	0.70	0.71	0.60	0.63
11	1	0	1	185.0	424.5	21.0	46.82	46.18	0.65	0.64	0.55	0.57
12	0	-1	0	169.5	386.0	21.0	48.26	48.31	0.65	0.65	0.55	0.54
13	1	1	0	185.0	463.0	17.5	6.65	5.57	0.40	0.40	0.40	0.40
14	0	-1	0	169.5	386.0	17.5	52.00	52.00	0.62	0.62	0.52	0.52
15	0	0	0	169.5	424.5	17.5	30.52	28.47	0.62	0.60	0.52	0.58
16	-1	0	0	154.0	424.5	17.5	6.67	6.32	0.52	0.52	0.42	0.44
17	1	0	0	185.0	424.5	17.5	40.18	42.11	0.62	0.63	0.64	0.60

Table 4: ANOVA results for the model representing WA (%)

Sources	Sum of Squares	Df	Mean Squares	F value	p-value [Prob >F]
Model	5831.52	9	647.95	288.01	<0.0001
X_1	2142.19	1	2142.19	952.19	<0.0001
X_2	1080.52	1	1080.52	480.26	< 0.0001
X_3	71.06	1	71.06	31.59	0.0008
X_1X_2	407.73	1	407.73	181.23	<0.0001
X_1X_3	97.32	1	97.32	43.26	0.0003
X_2X_3	136.20	1	136.20	60.54	0.0001
X_1^2	63.74	1	63.74	28.33	0.0011
X_2^2	61.02	1	61.02	27.12	0.0012
X_3^2	108.73	1	108.73	48.33	0.0002
Residual	15.75	7	2.25		
Lack of Fit	10.71	3	3.57	2.83	0.1702
Pure Error	5.04	4	1.26		
Cor Total	5847.27	16			

Table 5: ANOVA results for the model representing TS (%)

Sources	Sum of Squares	Df	Mean Squares	F value	p-value [Prob >F]
Model	0.16	9	0.018	132.32	<0.0001
X_1	0.019	1	0.019	149.83	<0.0001
X_2	0.053	1	0.053	387.03	<0.0001
X_3	3.632E-003	1	3.632E-003	26.48	0.0013
X_1X_2	8.970E-004	1	8.970E-004	6.54	0.0377
X_1X_3	2.277E-005	1	2.277E-005	0.17	0.0015
X_2X_3	3.5414E-003	1	3.5414E-003	25.62	0.0015
X_1^2	2.951E-003	1	2.951E-003	21.51	0.0024
X_2^2	5.163E-003	1	5.163E-003	37.64	0.0005
X_3^2	5.174E-004	1	5.174E-004	3.77	0.0932
Residual	9.60E-004	7	1.372E-004		
Lack of Fit	6.601E-004	3	2.200E-004	2.93	0.1627
Pure Error	3.00E-004	4	7.500E-005		
Cor Total	0.16	16			

Table 6: ANOVA results for the model representing LE (%)

Sources	Sum of Squares	Df	Mean Squares	F value	p value [Prob >F]
Model	0.11	9	0.013	9.02	0.0042
X_1	0.041	1	0.041	29.62	0.0010
X_2	0.010	1	0.010	7.56	0.0285
X_3	3.713E-003	1	3.713E-003	2.68	0.1459
X_1X_2	1.007E-003	1	1.007E-003	0.73	0.4224
X_1X_3	3.472E-004	1	3.472E-004	0.23	0.6322
X_2X_3	3.153E-003	1	3.153E-003	2.27	0.1754
X_1^2	0.012	1	0.012	8.83	0.0207
X_2^2	7.670E-003	1	7.670E-003	5.53	0.0510
X_3^2	1.989E-004	1	1.989E-004	0.14	0.7162
Residual	9.712E-003	7	1.387E-003		
Lack of Fit	5.237E-003	3	1.746E-003	1.56	0.3303
Pure Error	4.475E-003	4	1.119E-003		
Cor Total	0.12	16			

Statistical information for ANOVA shows that the models describing WA, TS, and LE had a high coefficient of determination (R^2), as shown in Table 7. This shows that the models could adequately represent the relationship between the chosen factors (stacking time, resin loading and amount of agro residue) and responses (WA, TS and LE). R^2 values of 0.99, 0.99 and 0.92 mean that the models could explain 99%, 99% and 92% of the variability observed in WA, TS and LE values, respectively. The adjusted R-square value of 0.98, 0.99 and 0.99 is in consonant with the R^2 values of the models. The standard deviations were relatively small compared to the mean, as shown in Table 7. The coefficient of variation was obtained for both models as 5.76, 2.08 and 7.31, respectively. This parameter shows the degree of precision with which the runs were carried out. The values obtained show high reliability, as recommended by Montgomery in 2005. The Adequate precision for both models indicates adequate signals meaning that the models can be used to navigate the design space (Cao et al., 2009).

Table 7: Statistical information for ANOVA

Parameter	Value		
	WA	TS	LE
R-Squared	0.99	0.99	0.92
Mean	26.03	0.56	0.51
Standard Deviation	1.50	0. 01	0. 04
CV %	5.76	2. 08	7.31
Adeq. Precision	50.68	39.37	10.20
Adjusted R-Square	0.98	0.99	0.99

Optimization of particle board production

Response surface methodology was used to optimize the particle board production variables. This was achieved by generating response surface plots showing the effects of board stacking time, resin loading and amount of agro residue on the WA, TS and LE of the boards produced. Figure 1 shows the effect of resin loading and stacking time on the WA of the particle boards. The trend observed shows that the WA decreased with an increase in the amount of resin loading and the stacking time used. The resin loading has been reported to determine the number of voids in the boards produced by Sekaluvu et al. (2014). Good adhesive quality resulting from adequate contact time between the resin and the agro residue particles has been cited for good board properties (Sekaluvu et al.,2014). This is because high resin loadings increase the bond contact between the particles, resulting in improved surface contact created when the particles are surrounded by a significant film of resin (Babatunde,2011) which could be responsible for the minimum value of physical properties of the board. Also, it was observed that the stacking time decreases the WA of the board due to the acclimatization of the board with the natural environment. A similar trend was observed in Figures 2 and 3 for TS and LE, respectively. Since WA, TS and LE are physical properties, the trend observed for each would be expected to be similar.

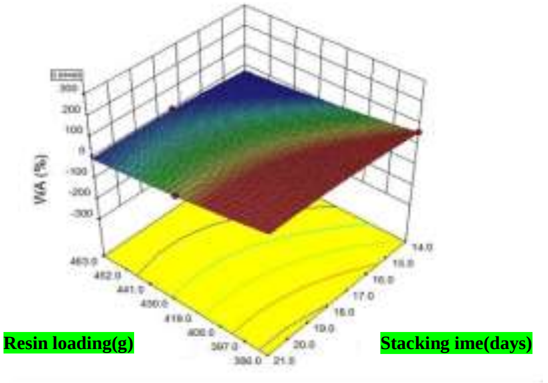

Figure 1. Effect of resin loading and stacking time on WA.

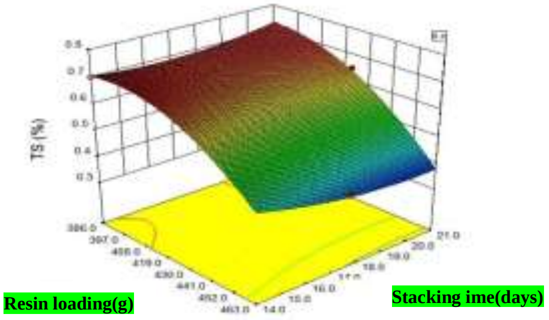

Figure 2. Effect of resin loading and stacking time on TS.

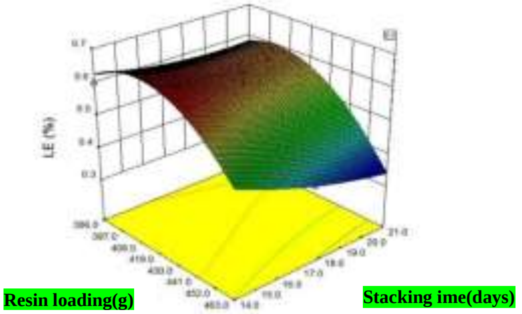

Figure 3. Effect of resin loading and stacking time on LE.

The effect of agro residue and stacking time on the WA is shown in Figure 4; an intermediate amount of agro residue(sawdust) was needed to produce particle boards with low WA values and the corresponding increase in stacking time. Since a constant agro residue to resin ratio was used, an intermediate amount of agro residue means more resin could produce the boards, enhancing the physical properties. The minimum value of WA observed in the particle board production could be due to the acclimatization of the board with the natural environment. For uniform distribution of the adhesive use with agro-residue, adequate stacking and contact time is required, this is because high resin loadings increase the bond contact between the particles, which in turn results in improved surface contact created when the particles are surrounded by a significant film of resin (Babatunde,2011). Since WA, TS and LE are physical properties, thus similar trend was observed in Figures 5 and 6 for TS and LE, respectively. The boards' stacking time has significantly influenced the boards' WA, TS and LE, as shown in Figures 5 and 6, respectively. This agrees with the results presented in Tables 4 – 7.

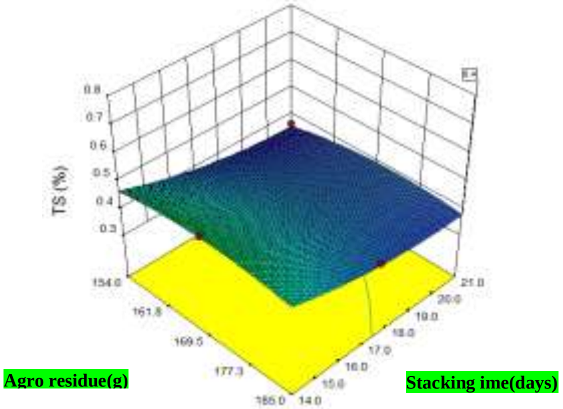

Figure 5. Effect of the amount of agro residue and stacking time on TS.

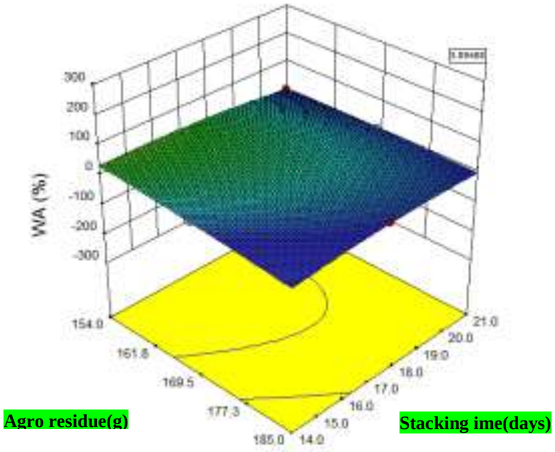

Figure 4. Effect of the amount of agro residue and stacking time on WA

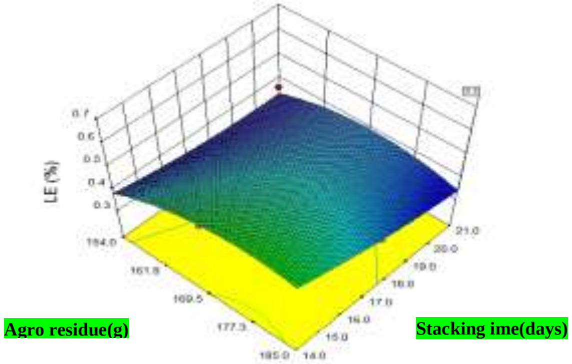

Figure 6. Effect of the Amount of agro residue and stacking time on LE.

The effect of agro residue and resin loading on the WA is shown in Figure 7 shows that an intermediate amount of sawdust was needed to produce particle boards with a minimum value of WA and a corresponding increase in the amount of resin used. Since a constant agro residue to resin ratio (1:2.5) was used, an intermediate amount of agro residue means more resin could produce the boards, enhancing the physical properties. An increase in the agro residue amount will significantly affect the WA by increasing the amount of resin used in producing the particleboards, as shown in Figure 7. Also, resin loading has been reported to determine the number of voids in the boards Sekaluvu et al. produced in 2014. When a low resin loading is used, the resin is mixed up with the agro residue particles leaving some voids. However, when the resin loading is increased, some of it is mixed with the agro residue particles to form the finish while the remainder fills up the voids that would otherwise be present in the finished product. A similar trend was observed in Figures 8 and 9 for TS and LE, respectively. A corresponding increase was observed in the amount of agro residue and resin loading, which is in consonant with the results presented in Tables 4, 5 and 6.

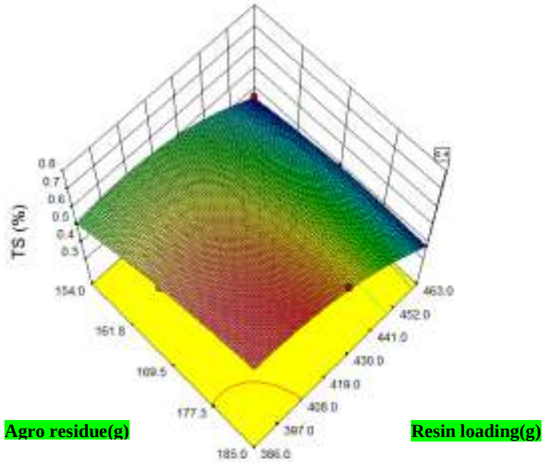

Figure 8. Effect of the amount of agro residue and resin loading on TS.

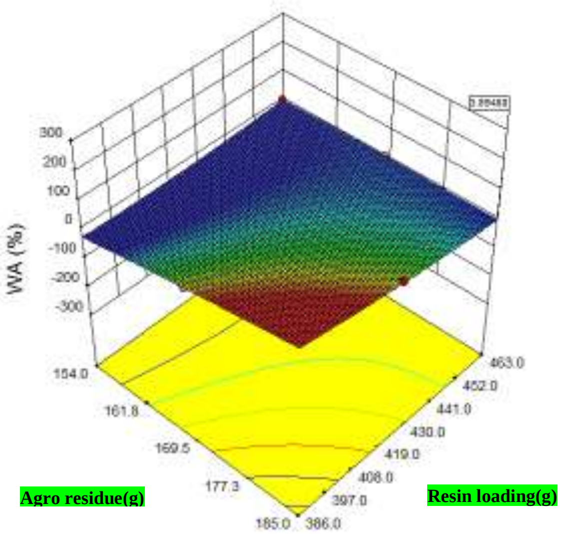

Figure 7. Effect of the amount of agro residue and resin loading on WA

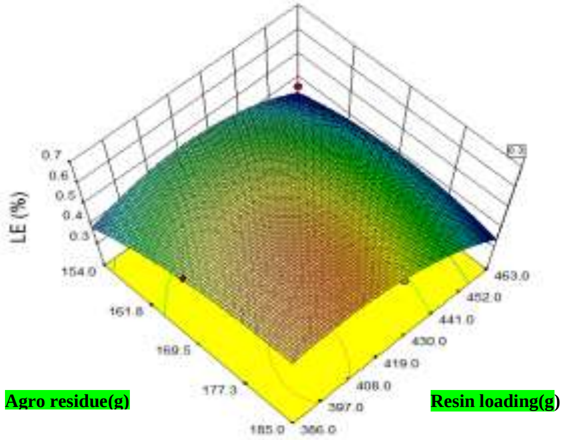

Figure 9. Effect of the Amount of Agro-residue and Resin Loading on LE.

The optimum levels of the independent variables and the responses (WA, TS and LE) were determined from numerical optimization of the statistical models (Equations 4, 5 and 6) and the top five results are shown in Table 8. The results show that the minimum values for WA, TS and LE were obtained at a stacking time of 21 days, a resin loading of 462.82 g and an agro residue loading of 185g. WA, TS and LE obtained at these optimized conditions were 4. 05%, 0.38% and 0.34%, respectively, with a model desirability of 0.897.

Table 8: Solutions for optimum conditions

Solution	Stacking time (days)	Resin loading (g)	Agro residue (g)	WA(%)	TS(%)	LE(%)	Desirability
1	21.00	462.82	185.00	4.05	0.38	0.34	0.897
2	20.53	463.00	185.00	5.60	0.38	0.35	0.886
3	21.00	461.69	185.00	5.03	0.39	0.881	0.881
4	21.00	463.00	154.00	3.71	0.35	0.33	0.872
5	21.00	462.53	154.00	3.35	0.35	0.34	0.872

Validation of Statistical Models

Three validation experimental runs were performed at the chosen optimum conditions to validate the statistical models representing physical properties (WA, TS and LE). The result shows that the minimum WA, TS and LE of 4.03%, 0.36% and 0.33%, respectively, were close to the predicted values of 4.05%, 0.38% and 0.34%, respectively. The excellent correlation between the predicted and measured values of these experiments shows the validity of statistical models.

Conclusion

The experiment design for response surface methodology has been demonstrated to be useful in optimizing the production process of the board. The stacking time, amount of agro residue and resin used influenced the board's physical properties, such as WA, TS and LE. Quadratic statistical models developed to represent WA, TS, and LE showed a good fit with the experimental data with R^2 values of 0.99, 0.99 and 0.92, respectively. The best particle board was produced at the optimized conditions, and it had a WA, TS and LE of 4.05(%), 0.38 (%) and 0.34 (%). This was achieved at a stacking time of 21 days, a resin loading of 462.82 g and an agro residue loading of 185.00 g. The particle board produced at the optimized conditions satisfied the American National Standard ANSI/A208.1-1999 specification for general-purpose particle boards.

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Conflict of Interest

The authors declare no conflict of interest, financial or otherwise.

References

Abdulkareem, SA; Raji, SA; Adeniyi, AG (2017). Development of particleboard from waste styrofoam and sawdust, *Niger, J. Technol. Dev.* (14):18. https://doi.org/10.4314/njtd.v14i1.3

Abhishek, N; Bikarama, PY; Soumyadeep, B; Debajyoti, B (2017). Recent Scenario of Solid Waste Management in India. World Scientific News (66):56-74.

Al-Fakih, A; Mohammed, BS; Liew, MS; Nikbakht, E (2019). Incorporation of waste materials in the manufacture of masonry bricks. *Journal of Building Engineering* (21):37-54. https://doi.org/10.1016/j.jobe.

Amenaghawon, NA; Nwaru, KI; Aisien, FA; Ogbeide, SE; Okieimen, CO (2013). Br. Biotechnol. J. (3): 236.

Amenaghawon, NA.; Osayuki-Aguebor, W; Okieimen, CO; (2016). *J. Mater. Environ. Sci. 7 (4): 1236-1244.*
American National Standard Institute. Particle board ANSI A208.1-1999 Table A 7: 1999.

Babatunde, A (2011). *J. Forest. Res.* (22): 111.

Cao, G; Ren, N; Wang, A; Lee, DJ; Guo, W; Liu, B; Feng, Y; Zhao, Q (2009). *Int. J. Hydrogen Energy*. (34):7182.

Emmanuel, MU; Edidiong, SS (2020). The Recycling of Sawdust Waste into Particleboard Using StarchBased Modified Adhesive. *Comm. in Physical Sci*. 6(1):760-766.

Eyide, O; Amenaghawon, NA; Modebe, LU; Mene, JA (2023). Optimization of Mechanical Properties of Bonded Particle Boards Produced From Agricultural Waste Wood Chips J. Appl. Sci. Environ. Manage. Vol. 27 (4) 733-740 April 2023 https://dx.doi.org/10.4314/jasem.v27i4.13

Fono-Tamo, RS; Idowu, OO; Koya, FO; (2014). Development of pulverized palm kernel shells-based particleboard, Int. *J. Mat. Mech. Eng.* 3 (3):54–61.

Harsavardhaa, A; Murugananandam, I (2017). Preparation and characteristic study of particleboard from solid waste. *14th Int'l conference on sci.& eng. (ICSET)*. 263(1):1001.

Hassan, BB; Awopetu, OO (2019). Production and Characterization of Particle Boards from Common Agro Wastes in Nigeria. *International Journal of Innovative Science and Research Technology*. ISSN No:-2456-2165

Ikubanni, PP; Adeleke, AA; Adediran, AA; Agboola, OO (2018). Physico-mechanical properties of particle boards produced from locally sourced materials. *Int. J. Eng. Res. Afr.* (39): 112–118.

Jacob, MO; Habeeb, OZ; Isa OE (2018). Sustainable wood waste management in Nigeria. *Environ. Socio.-econ. Stud*.4(3): 1-9.

Jannat, N; Hussien,A; Abdullah, B; Cotgrave, A (2020). Application of agro and non-agro waste materials for unfired earth blocks construction. *Construction and Building Materials* (254):102-119

Jannat, N; Latif Al-Mufti, RA; Hussein, A; Abdullah, B; Cotgrave, A; (2021) Influences of Agro-wastes on the Physico-mechanical and Durability Properties of Unfired Clay Blocks. *Construction and Building Materials.* ISSN 0950-0618. pp318

Jargalsaikhan, O; Saracoğlu, N; (2008). *Chem. Eng. Commun*. (196):93.

Laborel-Preneron, A; Aubert, JE; Magniont, C; Tribout, AB (2016). Plant aggregates and fibres in earth construction materials. *Construction and Building Materials* (111): 719-734. https://doi.org/10.1016/j.conbuildmat.

Lacovidou, E; Milliward-Hoppins, J; Busch, J; Purnel, P; Velis, CA; Hahladakis, JN; Zwirner, O; Brown, A (2017). A pathway to a circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. *J. cleaner production*. (168):1279-1288

Lias, H; Kasim, J; Johari,NAN; Mokhtar, ILM (2018). Influence of board density and particle sizes on the homogenous particleboard properties from kelempayan (Neolamarckia cadamba). *Int. J. Latest Res. Sci. Technol.* 3 (6):173–176

Melo, RR; Stangerlin, DM; Santana, RRC; Pedrosa, TD (2014). Physical and mechanical properties of particleboard manufactured from wood, bamboo and rice husk, *Mat. J.* Res.17 (3):682–686.

Montgomery, DC (2005). Design and Analysis of Experiments. 6. ed. *New York: John Wiley & Sons, Inc.*

Odeyemi, SO; Abdulwahab, R; Adeniyi, AG; Atoyebi, OD (2020). Physical and mechanical properties of cement-bonded particle board produced from African balsam tree (Populous Balsamifera) and periwinkle shell residues, Published by Elsevier Ltd. https://doi.org/10.1016/j.rineng.2020.100126

Odusote, JK; Onowuma, SA; Fodeke, EA (2016). Production of paperboard briquette using waste paper and sawdust. *J. Eng.* Res.13 (1):80–88.

Sahin, A; Tasdemir, HM; Karabulut, AF; Gürü, M (2017). Mechanical and thermal properties of particleboard manufactured from waste peach nutshell with glass powder, *Arab. J. Sci. Eng.* (42):1559–1568.

Sekaluvu L; Tumutegyereize P; Kiggund , N (2014). *Waste Biomass valor.J*. (5):27.

Sotannde, O.A; Oluwadare, A.O; Ogedoh ,O; Adeogun, P.F (2012). *J., Eng. Sci. Technol*. 6:732

Tomas, U; Ganiron, Jr; Nieves, U; Tommy, UG (2017). Recycling of Waste Coconut Shells as Substitute for Aggregates in Mix Proportioning of Concrete Hollow Blocks. *World Scientific News* 77(2):103-119

U.S. Environmental Protection Agency (USEPA) (2023). https://www.epa.gov/hw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions

Wang, SY; Yang, TH; Lin, LT; Lin, CJ; Tsai, MJ (2014). Fire-retardant-treated low- formaldehyde-emission particleboard made from recycled wood waste. *Bioresour. Technol*. Rep. 99 (6):2072–2077.

Wang, D; Sun, SX (2002). Low-density particleboard from wheat straw and corn pith. *Industrial Crop Production J*. (15): 43-50.

Young G. C (2010). Municipal solid waste to energy conversion processes: Wiley Blackwell.