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Optimization of Mechanical Properties of Bonded Particle Boards Produced From Agricultural Waste Wood Chips

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ABSTRACT: The aim of this research work was to optimize the production of particle boards from agricultural waste (wood chips). The mechanical properties investigated were the modulus of elasticity (MOE) and modulus of rupture (MOR). The production of particle boards was investigated under the following conditions: stacking time (14-21days), 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 (MOE and MOR) and the independent variables. Both models showed significant fit with experimental data with R^2 values of 0.99 and 0.97 respectively. Analysis of variance (ANOVA) results showed that MOE and MOR were influenced by the stacking time, amount of resin and agro residue used. Response surface methodology (RSM) was used to optimize the MOE and MOR and the optimization results showed that the maximum MOE and MOR values of 1114.09N/mm^2 and 9.34 N/mm^2 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.

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Waste generation has caused huge burden on our environment (Emmanuel and Edidiong, 2020). According to Young *et al*., (2010), Industrial, urbanization and agricultural activities has generated a lot of waste in our environment. Previously, great attention is directed toward the wood industries, which have produced a lot of toxic waste that are released into our environment (Harshavardhan and Muruganandam (2017). Wood rich in heavy metals possess pollutants that are released into the soil or surrounding water bodies via decay or leaching processes (Sardar *et al*., 2013). One of the environmental challenges associated with wood industries in modern society is the utilization of wood particles (wood chips) into useful products. The common features of wood industries are associated with large amount of forest waste residue which could be utilized, marketed or properly disposed of. In Nigeria, this residue is generally regarded as waste and they are disposed via burning practices, dumping in water bodies or dumping in an open area which constitutes environmental pollution. Sawmills in Nigeria generated over 1,000,000 m^3 of wood waste in 2010 while about 5000 m^3 of waste was generated in plywood mills (Jacob *et al*., 2016). Nigeria generates about 1.8 million tons to 5.2 million tons of wood

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wastes annually (Jacob *et al*., 2016). The impact of improper disposal of wood particles on the environment affects both the aquatic and terrestrial ecosystems. Also burning of these wood wastes releases greenhouse gases into the atmosphere causing various health issues. Reuse/recycling of these wood residues in Nigeria will reduce the pressure on our ever decreasing forests, reduce environmental pollution, create wealth and employment (Jacob *et al*., 2016). Saw dust is greatly available in Nigeria especially in the southern part of the country and their disposal has produced negative impact on our environment. Wastes in the wood industry could be in solid form, which are unwanted materials produced during the manufacturing process. Wood waste consists of wood chips and particles generated from the industrial or small scale processing of wood construction and demolition activities and broken down wood products (Jacob *et al*., 2016). Wood waste management approaches are very necessary in addressing these wastes generated from wood industries. This can be achieved via resource recycling which involves turning wood chips into valuable product such as particle board (Harshavardhan *et al*., 2017; Emmanuel *et al*., 2020). Waste management process is profitable when it involves resource recovery, reuse and recycling (Lacovidou *et al*., 2017). Particle board is a composite board manufactured from a mixture of wood fiber, plastic, cement, and different types of binding agents such as synthetic resin and other suitable binders, bonded together under the application of heat and pressure (Ikubanni *et al*., 2018; Odusote *et al*., 2016). Composite boards can also 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, rice husks, cotton stalks, rice straw etc. (Ikubanni, *et al*.,2018; Odusote, *et al*., 2016). These discrete particles are bonded with a suitable adhesive and compressed to form composite boards (Melo *et al*., 2014). The importance of composite boards along with particle boards cannot be overemphasized as evident in their use for structures, home constructions, furniture making, flooring, wall partitions, cabinets, tables, counters and desktops, office dividers, ceilings, core materials for doors and so on (Wang and Sun., 2002; Wang, *et al*., 2008; Fono-Tamo *et al*., 2014). Previous work by Amenaghawon *et al*., (2016), showed that the modulus of rupture (MOR) and modulus of elasticity (MOE) of particle boards were influenced by the amount of resin and agro residue used. In Nigeria today, one of the challenges associated with construction industry is continuous increase in the price of building materials (Amenaghawon *et al*., 2016). This challenge can be alleviated, when the necessary waste management approaches are taken into consideration through valorization of the wood waste. It is worthy to note that, numerous types of waste materials have been investigated for the production of both the common and composite particleboard. From recent study by Kelvin *et al*., (2018), composite particleboard was produced using urea-formaldehyde (URF) resin and sawdust. Also Harshavardhan *et al*., (2017), particleboard characterized from municipal dry wastes, plant waste, and sawdust, revealed that the tensile, compressive and flexural strengths of the board is in conformity other country standard. Other feedstock materials that could be used along with sawdust for the production of composite particleboard include bamboo (Melo *et al*., 2014), water-melon peels (Lias *et al*., 2014), peanut shell with glass powder (Sahin *et al*., 2017), blend of corn cobs and cassava stalk (Amenaghawon *et al*., 2016) and so on. In another study by Akinyemi *et al*., (2019), particleboards produced from wood saw dust using native cassava modified with 25 % glutaraldehyde solution produced board with peak value of modulus of elasticity and modulus of rupture of 3232 Nm^2 and 35.7 Nm^2 respectively. To the best of our knowledge, none of these studies have attempted to optimise the mechanical properties of the particle board produced from these wood particles. Thus, the objective of this study is optimization of mechanical properties of bonded particle boards produced from agricultural waste wood chips using top bond adhesive as a binder.

MATERIALS AND METHODS

Materials collection and pretreatment: The agro residues used in this study, wood chips were obtained from saw mill at Uselu market in Egor local Government Area, Edo state, Nigeria. Top bond adhesive used as binder were obtained from Uselu market in Egor local Government Area of Edo state of Nigeria. The residues (wood chips) were properly washed and sun dried for 2months to remove sand, 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. In order to ensure and enhance 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). This was done in order to ensure proper setting of the boards. The treated residues materials were separately air dried to attain approximately 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 mechanical properties of the particle boards 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 the exploration of quadratic response surfaces and this design generates a second degree polynomial model which 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 center point. The design for the production of particle boards 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).

$$x_i = \frac{X_i - X_o}{\Delta X_i} \qquad (2)$$

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 center 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).

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

where Y_i is the dependent variable or predicted response, X_i and X_j are the independent variables, b_o is 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 models for MOR and MOE 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 optimisation 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 design given in table 2, by design Expert through the use of Box Behnken Design. After pretreatment, the feedstock residue (wood chip) was thoroughly mixed with the adhesive (in the ratio 1:2.5) to obtain a lump free matrix. The resulting material was then put in a mat forming box with dimensions 0.3m x 0.3m x 0.006m. A manual press machine was used to make a prepressing at 0.78 N/mm^2. The box was then put in a hydraulic press and the boards were made by using an 8minute press closing time at a pressure of 1.23x 10^6 N/mm^2 (Mendes, 2009). The mat forming box was covered with polythene sheet prior to board formation to prevent the sticking of the boards onto 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 acclimatisation 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. Mechanical tests (modulus of elasticity (MOE) and modulus of rapture (MOR)) as well as physical tests (thickness swelling (TS), water absorption (WA) and linear expansivity) were carried out on the experimental boards according to standard methods of ASTM D1037 and DIN 52362. In this work, only the mechanical properties were evaluated.

RESULTS AND DISCUSSION

Statistical analysis: The Box-Behnken design was used to analysis the results as shown in Table 3. Equations (4) and (5) were obtained after applying multiple regression analysis to the experimental data. These second degree polynomial equations were used to estimate the responses, MOE and MOR respectively.

$$Y_2= +600.94 - 61.82\, X_1+ 46.27\, X_2+ 116.69\, X_3 + 235.99\, X_1X_2- 107.25\, X_1X_3+ 94.06\, X_2X_3+77.87\, X_1^2+ 55.5\, X_2^2+ 58.15\, X_3^2 \qquad (4)$$

$$Y_1=+4.63- 0.73\, X_1 + 1.39\, X_2 + 1.11X_3 +1.88X_1X_2 - 1.27X_1X_3 + 0.53X_2X_3 + 0.96X_1^2+ 0.72\, X_2^2+ 0.13\, X_3^2 \qquad (5)$$

The values of MOR and MOE predicted by Equations (4) and (5) are given in Table 3 along with the experimental data. The significance of the fit of the equations representing MOE and MOR was assessed by carrying out analysis of variance (ANOVA). ANOVA results show that the models for MOR and MOE were statistically significant with p values of <0.0001 and <0.0001 respectively as shown in Tables 4 and 5. Both models did not show lack of fit as seen from their "lack of fit" p values (0.1071and 0.2474 respectively). For both models, the terms representing resin loading, stacking time and amount of agro residues were significant indicating that they significantly influence the MOR and MOE of the boards produced. Statistical information for ANOVA shows that the models describing MOE and MOR had high coefficient of determination (R^2) as shown in Table 6. This shows that the models were able to adequately represent the relationship between the chosen factors (stacking time, resin loading and amount of agro residue) and responses (MOE and MOR).

Table 3: Box Behnken Design Matrix for the optimization variables and response values of Modulus of Rupture and Modulus of Elasticity

Run	Variables						Response			
	Coded levels			Actual values			MOE(N/mm^2)		MOR(N/mm^2)	
	X1	X2	X3	X1	X2	X3	Actual	Actual	Actual	Actual
1	0	0	0	169.5	424.5	17.5	589.12	600.94	4.66	4.63
2	0	0	0	169.5	424.5	17.5	589.12	600.94	4.66	4.63
3	0	1	-1	169.5	463.0	14.0	562.13	550.15	5.47	5.23
4	0	0	0	169.5	424.5	17.5	598.14	600.94	4.50	4.63
5	0	-1	-1	169.5	386.0	14.0	654.17	645.74	3.64	3.51
6	0	1	1	169.5	463.0	21.0	969.62	971.64	8.49	8.51
7	-1	1	1	154.0	463.0	21.0	976.92	982.60	9.44	9.59
8	-1	0	0	154.0	424.5	17.5	754.62	740.62	7.12	6.32
9	-1	0	-1	154.0	424.5	14.0	553.02	574.83	3.63	4.07
10	1	-1	-1	185.0	386.0	14.0	534.45	533.05	3.21	3.14
11	1	0	1	185.0	424.5	21.0	702.10	684.56	5.21	4.84
12	0	-1	0	169.5	386.0	21.0	681.15	690.99	4.46	4.66
13	1	1	0	185.0	463.0	17.5	950.50	954.78	8.79	8.86
14	0	-1	0	169.5	386.0	17.5	610.21	610.21	3.96	3.96
15	0	0	0	169.5	424.5	17.5	618.81	600.94	4.57	4.63
16	-1	0	0	154.0	424.5	17.5	754.12	740.62	6.12	6.32
17	1	0	0	185.0	424.5	17.5	602.31	616.98	4.50	4.87

R^2 values of 0.99 and 0.97 means that the models were able to explain 99% and 97% of the variability observed in the values of MOR and MOE respectively. The standard deviations were observed to be relatively small compared to the mean. The coefficient of variation was obtained for both models as 2.66 and 7.99 respectively. This parameter shows the degree of precision with which the runs were carried out. The values obtained show a high reliability as recommended by Montgomery (Montgomery, 2005).

The Adequate precision for both models indicate adequate signals meaning that the models can be used to navigate the design space (Cao *et al*., 2009).

Optimization of particle board production:
Response Surface Methodology was used to optimise 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 MOE and MOR of the boards produced.

Table 4: ANOVA results for model representing MOE (N/mm^2)

Sources	Sum of Squares	Df	Mean Squares	F value	p value [Prob >F]
Model	3.430E+005	9	38109.9	113.4	<0.000
X_1	25573.76	1	25573.7	76.14	<0.000
X_2	11187.73	1	11187.7	33.31	0.0007
X_3	99412.84	1	99412.8	295.9	<0.000
X_1X_2	23157.80	1	23157.8	68.94	<0.000
X_1X_3	6133.00	1	6133.00	18.26	0.0037
X_2X_3	36477.36	1	36477.3	108.6	<0.000
X_1^2	21373.65	1	21373.6	63.63	<0.000
X_2^2	2247.70	1	2247.76	6.69	0.0361
X_3^2	2331.38	1	2331.38	6.94	0.0337
Residua	1762.86	7	335.89		
Lack of	1762.86	3	587.62	3.99	0.1071
Pure	588.37	4	147.09		
Cor Total	3.453E+005	16			

Table 5: ANOVA results for model representing MOR (N/mm^2)

Sources	Sum of Squares	Df	Mean Squares	F value	p value [Prob >F]
Model	56.92	9	6.32	33.52	<0.0001
X_1	3.53	1	3.53	18.69	0.0035
X_2	10.12	1	10.12	53.62	0.0002
X_3	8.97	1	8.97	47.54	0.002
X_1X_2	1.47	1	1.47	7.81	0.0268
X_1X_3	0.86	1	0.86	4.55	0.0704
X_2X_3	1.17	1	1.17	6.18	0.0419
X_1^2	3.28	1	3.28	17.37	0.0042
X_2^2	0.37	1	0.37	1.99	0.2015
X_3^2	0.011	1	0.011	0.059	0.8150
Residual	1.32	1	0.19		
Lack of	0.80	3	0.27	2.07	0.2474
Pure	0.52	4	0.13		
Cor Total	58.24	16			

Table 6: Statistical information for ANOVA

Parameter	Value	
	MOE	MOR
R-Squared	0.99	0.97
Mean	688.27	5.44
Standard Deviation	18.33	0.43
C.V %	2.66	7.99
Adeq. Precision	31.98	19.37

Figure 1 shows the effect of amount of agro residue and resin loading on the MOE of the particle boards. The trend observed shows that the MOE increased with increase in the amount of agro residue and the amount of resin used. This shows that there was adequate adhesion between the resin and the agro residue resulting in the increased MOE (Yimsamerjit *et al*., 2007). Previous studies have revealed that to manufacture particle boards with high MOE, more amount of resin loading needs to be added (Amenaghawon *et al*.,2016; Mendes *et al*., 2009; Aisien *et al*., 2013;). Amenaghawon *et al*., (2016), reported that the modulus of rupture (MOR) and modulus of elasticity (MOE) of particle boards were influenced by the amount of resin and agro residue used. The amount of resin has been reported to determine the number of voids present in the particle boards manufactured (Sekaluvu *et al*., 2014). When small amount of resin loading is used, the mixing of the resin with agro residue particles leave some voids in the board. However, when the resin loading is increased, some of it is mixed with the agro residue particles to form the finish product while the left over fills up the voids that would otherwise be present in the finished product. Figure 1 also shows that maximum amount of agro residue was needed to produce particle boards with high MOE values. Since a constant agro residue to resin ratio was used, maximum amount of agro residue will required more resin to be used to produce the boards thus resulting in the enhancement of the mechanical properties. Similar trends in figure 1 for MOE, was observed in figure 5 for MOR. The effect of stacking time and agro residue on the MOE is shown in Figure 2. With regards to agro residue, a similar trend to Figure 1 was observed showing that the utilization of high agro residue enhanced the MOE of the boards produced. The stacking time of the boards have significant effect on the MOE with respect to the amount of agro residue used. This supports the observation made in Table 4 that the model term representing stacking time had a p-value greater than 0.05 showing that it was not significant. Similar trend was observed in figure 4 for MOR.

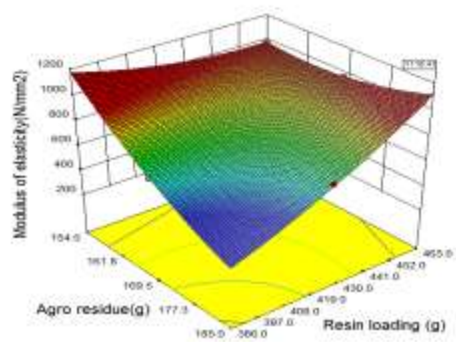

Fig 1. Effect of amount of agro residue and resin loading on MOE

Figure 3 shows the effect of resin loading and stacking time on MOE. The trend observed are similar to those presented in Figures 1 and 2 respectively. The MOE of the boards was observed to increase with increase in resin loading. Good adhesive quality resulting from adequate contact time between the resin and the agro residue particles has been cited as a reason for high MOE values (Sekaluvu *et al*., 2014). This follows from the fact that 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). Also it was observed that as the stacking time increased, the MOE of the board increased, which is due to acclimatization of the board with the natural environment. Similar trend was observed in figure 4 for MOR. Since MOE and MOR are both mechanical properties, the trend observed for both would be expected to be similar. Both measures of mechanical strength of particle boards have been reported to be influenced by particle geometry and amount of resin (Bekalo, 2010; Saffari, 2011).

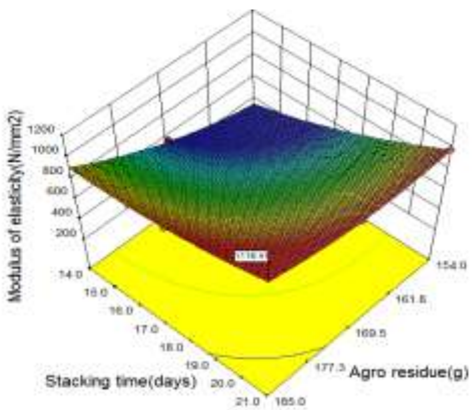

Fig 2. Effect of stacking time and amount of agro residue on MOE

The stacking time of the boards have significantly influenced the MOE and MOR of the boards as shown in Figures 3 and 4 respectively. This is in agreement with the results presented in Tables 4 and 5. The requirement for agro residue-based particle boards is high MOR and MOE. Figure 5 shows that high MOR values were obtained when high levels of agro residue were used. Since a fixed ratio of agro residue to resin was used in producing the boards. The optimum levels of the independent variables and the responses (MOE and MOR) were determined from numerical optimization of the statistical models (Equations 5 and 6) and the top five results are shown in Table 7. The results show that the maximum MOE and MOR were obtained at a stacking time of 21 days, a resin loading of 462.82 g and an agro residue loading of 185g. The values of MOE and MOR obtained at these optimised conditions were 1114.09 N/mm^2 and 9.34 N/mm^2 respectively with a desirability of 0.897. The American National Standard Institute ANSI/A208.1-1999 specifies a minimum MOE and MOR of 550 N/mm^2 and 3 N/mm^2 respectively for general purpose particle boards. The optimum MOE and MOR of the particle boards produced from the agro residues was found to satisfy this requirement as they had MOE and MOR values which were higher than the minimum standard.

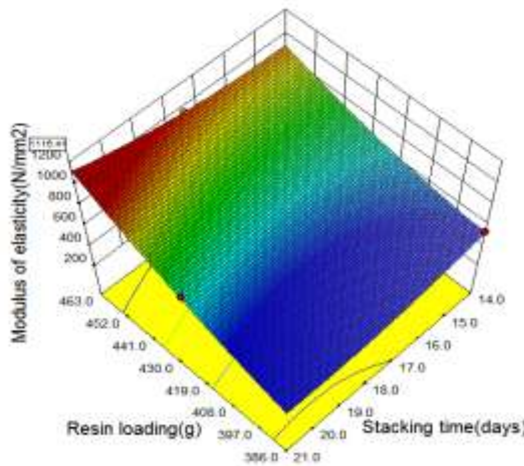

Fig 3. Effect of resin loading and stacking time on MOE

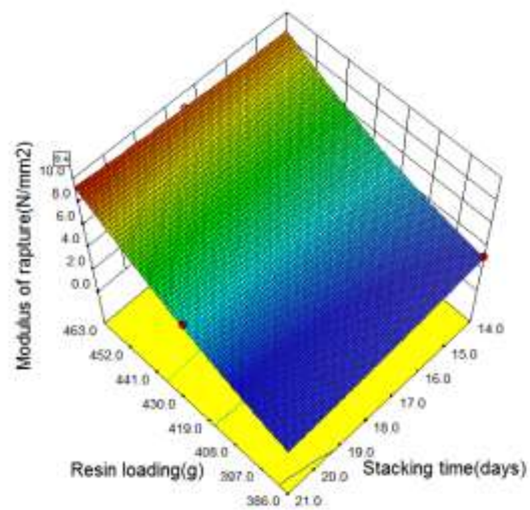

Fig 4. Effect of resin loading and stacking time on MOR

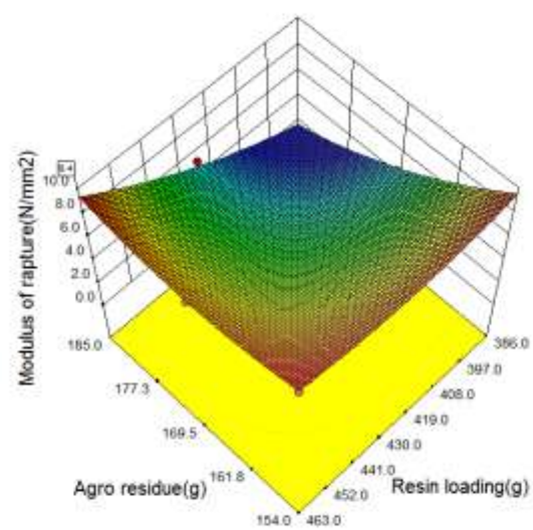

Fig 5. Effect of amount of agro residue and resin loading on MOR

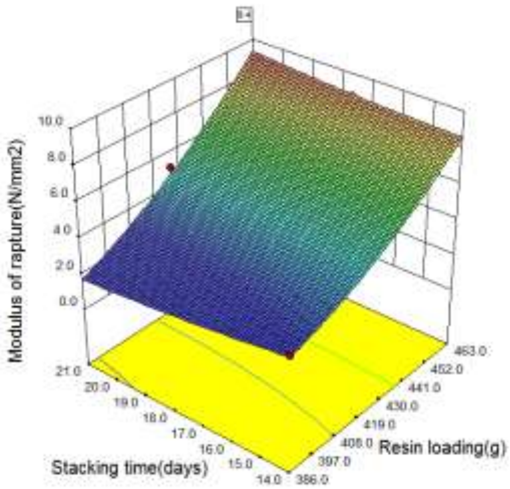

Fig 6. Effect of stacking time and amount of agro residue on MOR

Table 7: Solutions for optimum conditions

Solution	Stacking time (days)	Resin loading (g)	Agro residue (g)	MOE	MOR	Desirability
1	21.00	462.82	185.00	1114.09	9.34	0.897
2	20.53	463.00	185.00	1087.63	9.28	0.886
3	21.00	461.69	185.00	1099.93	9.18	0.881
4	21.00	463.00	154.00	982.59	9.59	0.872
5	21.00	462.53	154.00	982.41	9.57	0.872

Validation of Statistical Models: Three validation experimental runs were performed at the chosen optimum conditions to validate the statistical models representing Mechanical (MOR and MOE) properties. The result shows that the maximum MOR and MOE values of 9.32 N/mm^2 and 1113.57 N/mm^2 obtained were close to the predicted values of 9.34 N/mm^2 and 1114.09 N/mm^2. The excellent correlation between the predicted and measured values of these experiments shows the validity of statistical models.

Conclusions: Mechanical properties of the board such as MOE and MOR were influenced at a stacking time of 21 days, a resin loading of 462.82 g and an agro residue loading of 185.00 g. Quadratic statistical models developed to represent MOE and MOR showed a good fit with the experimental data with R^2 values of 0.99 and 0.97 respectively. The best particle board was produced at the optimised conditions and it had a MOE and MOR of 1114.09 N/mm^2 and 9.34 N/mm^2; which is in conformity with the American National Standard ANSI/A208.1-1999 specification for general purpose particle boards.

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