Investigating the Effect of Particle Slenderness Ratio on Optimizing the Mechanical Properties of Particleboard Using the Response Surface Method

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Restricted formaldehyde gas emissions and a scarcity of lignocellulosic raw materials have particleboard companies in Iran concerned about raw materials and adhesive use. The particle slenderness ratio is one of the main parameters that leads to the required mechanical characteristics of particleboard, together with the simultaneous decrease of density (raw materials) and the quantity of adhesive. The objective of this study was to evaluate the mechanical properties of particleboard composed of poplar particles with variables of density, adhesive quantity, and slenderness ratio using response surface technique. The variables were then optimized for the examined responses according to the EN 312-3 (1993) standard for the manufacturing of particleboard for domestic use as well as home and office furniture. Particleboard with minimum allowable properties according to EN 312-3 (MOR = 11 MPa, MOE = 1.6 GPa, and IB = 0.35 MPa) with a density of 0.65 g/cm^3, adhesive percentage of 10.54, and a slenderness ratio of 37.5 can be produced, according to optimization findings. Through raising the density to 0.69 g/cm^3 and the slenderness ratio to 46.99, the quantity of adhesive utilized in particleboard manufacturing could be decreased from 10.54 to 8.9% while keeping the minimum allowable resistances of EN 312-3 (1993) standard.

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INTRODUCTION

Under pressure and hot-pressing, particleboard is made from lignocellulosic materials with urea formaldehyde, melamine formaldehyde, and phenol formaldehyde adhesives (Farrokhpayam *et al.* 2016). Mordor Intelligence, one of the world's top market research firms, examined global wood chip output from 2019 through 2024. Accordingly, through 2024, Iran’s particleboard output and consumption will continue to rise (Mordor Intelligence 2020). Because Iran’s environment is dry and semi-arid, finding a balance between the shortage of wood supplies and the need to conserve forests and sustain the wood and paper industries has become a major concern. The particleboard’s weight is nearly entirely made up of lignocellulosic particles and resin. Therefore, resin content and wood particles are the largest cost factor in the production of particleboard. Based on information from Benthien (2022) on the cost structure for wood-based materials, the share of costs for prepared particles and adhesive are 68.9% of the total costs. On the other hand, reducing formaldehyde-based resins in particleboard manufacture reduces formaldehyde gas emissions in particleboard usage situations (Zhang *et al.* 2018). The State of California (2008) and the International Agency for Research on Cancer (IARC) have declared formaldehyde to be a carcinogen (Salem and Bohm 2013). The European Union, the United States, China, and Japan have rules governing the allowed levels of formaldehyde (FE) emissions from wood and wood products. Future legislation will surely emphasize items that produce formaldehyde gas (Salthammer *et al.* 2010). As a result, improving the strength of particleboard by raising the resin percentage and density of the final product due to higher manufacturing costs, increased formaldehyde emissions in the environment, and board weight is not a viable option for manufacturers and customers. In contrast, reduced adhesive consumption and raw material consumption must not to adversely affect particleboard strength parameters, such as flexural modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB), because customers are hesitant in this situation. They will not use it and will replace the use of particleboard with other similar products. Particle size optimization is one method for reducing resin and raw material usage while maintaining particleboard mechanical characteristics (Li *et al.* 2010; Juliana *et al.* 2012; Fasina 2013; Atta-Obeng and Fasina 2013; Cosereanu *et al.* 2015; Farrokhpayam *et al.* 2016; Bazzetto *et al.* 2019).

The ultimate qualities of the particleboard are determined by the length, width, and thickness of the particles. The particle slenderness ratio is the most significant dimensionless parameter explored to study the effect of particle size on particleboard qualities. The particle slenderness ratio is calculated as the length to thickness ratio (Semple and Smith 2006; Sackey and Smith 2009; Arabi *et al.* 2011b).

According to Semple and Smith (2006), replacing 20% of fine-grained wood with coarse-grained wood may boost internal bonding up to 40% and edge-to-edge screw holding capability up to 18% in particleboard. According to previous research, chips with a higher slenderness ratio improved the rupture modulus and elastic modulus of particleboard more than chips with a lower slenderness ratio, with the same increase in adhesive percentage. This is because bigger wood chips have a smaller specific surface area and better adhesive dispersion on the surface and between the particles. Because bigger particles with a lower specific surface area acquire more resin than smaller particles under the same circumstances, it further increases MOR and MOE values (Semple and Smith 2006; Sackey and Smith 2009; Arabi *et al.* 2011a). Additionally, Arabi *et al.* (2011b) also found that an increase in particle slenderness ratio on the MOR and the MOE compensated for the negative effects of density reduction and resin content reduction on particleboard mechanical characteristics. Juliana *et al.* (2012) evaluated the mechanical attributes of particleboard employing core kenaf particles (nearly rectangular) against bast kenaf particles (almost annular) in conjunction with rubber wood particles. The findings revealed that when rectangular core kenaf particles were combined with rubber wood particles, the mechanical characteristics of particleboards were significantly enhanced. Li *et al.* (2010) achieved similar results in investigating the effect of particle size on the mechanical properties of particleboard.

The effect of particle size on particleboard has been extensively studied; recently, analysis of adhesive distribution over particles according to their size and potential savings from particle surface determination was studied by Benthien *et al.* (2022). Their examination of the distribution of the adhesive over the particles surface showed that smaller particle sizes tended to be more heavily coated with adhesive. Fehrmann *et al.* 2022 showed that the internal bond (IB) performance increased in most ultra-low-density hemp hurd comprising coarse particles and declined with the addition of smaller particle sizes. Istek *et al.* (2018) reported, as the chip size increases, the bending and elasticity strength increases and the change in chip size in the surface layers did not cause a significant increase in IB strength. Chaloupková *et al.* (2018) investigated the particle size distribution analysis of pine sawdust fractions (4, 8, and 12 mm) was conducted using the photo-optical analyzer based on digital image processing and the conventional method based on sieving. They reported that the procedure of sieve analysis is easy and standardized; on the contrary the results were less accurate and consistent owing to the non-spherical particle shape. So, it is important to understand the size (length, width, and thickness), shape and volume of the wood particle and used them for optimization the wood-based composite production (Shanthi *et al.* 2014).

The response surface method (RMS) is a suitable approach for optimizing board strength attributes. RSM is a collection of statistical and mathematical tools for process development, improvement, and optimization that assesses the links between empirically controlled influencers and the predicted outcomes for one or more variables (Jensen 2017). The ability to carry out an optimization with fewer experimental conditions, the development of a statistical model for the desired output variables, the evaluation of the relationship between factors and responses, and the optimization of responses based on constraints are the most important advantages of the response surface method compared to other methods (Malik and Rashid 2000). Because there are many variables in particleboard manufacturing, such as density, moisture content, percent adhesive employed, press temperature, press time, wood type composition, and so on, it is difficult to optimize these variables to enhance the final product's quality. There are several benefits to understanding the link between the elements influencing particleboard quality and developing a mathematical model to forecast the features of this product based on mathematical models in the industrial manufacturing of the product. For industry owners and customers, improving production quality control, boosting production speed, cutting costs by optimizing variables and employing the least efficient materials are desired outcomes.

Another benefit of adopting the RSM is that the utility function could optimize structural and process variables in research and industrial operations to achieve the desired outcome (Laghrabli *et al.* 2017). The utility function is a simple mathematical approach for determining the optimum input and output parameters (response) that are conducted simultaneously, utilizing the level of the optimal input parameters (Derringer and Suich 1980). The utility function turns the answer (y_n) into a single utility function (d_i) with a range of 0 to 1. Desirability 1 indicates the highest level of response, while desirability 0 indicates the lowest level of reaction. Plywood (Lepine *et al.* 2001; Yu *et al.* 2015; Ruey *et al.* 2016), particleboard (Sacker and Smith 2010; Islam *et al.* 2012; Nazerian *et al.* 2016), fiber board (Kumar *et al.* 2017; Song *et al.* 2018; Nazirian *et al.* 2018; Li *et al.* 2019), and wood-rubber composite (Sofina-E-Arab and Islam 2015) were optimized and predicted using the RSM method. Chen *et al.* (2013b) used RSM to improve the soy flour adhesive preparation parameters for plywood manufacture. Gao *et al.* (2019) optimized bamboo plywood mechanical characteristics and evaluated the impact of several process factors on bamboo plywood mechanical properties. Previous investigations have shown that particle size substantially impacts the physical and mechanical characteristics of particleboards. However, no research has been conducted on particle size optimization and control to minimize the density and percentage of particleboard adhesive without affecting the mechanical qualities of the board. Therefore, the aim of this study was to predict the mechanical properties of particleboard (MOR, MOE, and IB) using RSM based on the central composite design, according to EN 312-3 (1993) standard with minimal consumption of glue and raw materials with controlling the slenderness ratio of particles.

EXPERIMENTAL

Experimental Design

The response surface method's central composite design (CCD) was employed in this study. The maximum and lowest limits of independent variables with codes (1+) and (1-), as well as its middle level with code zero, were defined in this respect. The responses were fed as input data into the Design-Expert software (Stat-Ease, Inc., version 12, Minneapolis, USA). Therefore, as the zero or middle level (0), the third level is a value between the lowest and maximum. Indeed, levels outside the three levels are efficiently programmed if they are identified between these levels. The Face Centered Composite Design (FCCD) design of the response level approach was employed in this research because each variable has three levels. For analysis, Design Expert 13 software was employed. The process variables and the codes used for the response level approach are shown in Table 1. Table 1 shows the low-density limit (0.65 g/cm^3) with code -1, the medium limit (0.70) with zero code, and the high-density limit (0.75 g/cm^3) with code +1. Table 1 also includes additional codes relating to the adhesive and slenderness ratio proportion with the specified codes. This research included 9 samples as focal points. The boards were made from poplar (*Populus alba*). Small-diameter logs of poplar were cut into blocks of 50 mm×50 mm×10 mm and then ground with a laboratory hammer mill. Particles were dried to a moisture content of less than 3%. After drying, the particles were sifted through three hand-held screens with 5, 8, and 12 mesh. The length of 5 g screened particles for each particle size (+5; −5 +8; -8 +12) were measured 55.1, 28.4, and 13.98 mm with a micrometer caliper, yielding three particle size levels with slenderness ratios of 47, 30, and 13, respectively.

Table 1. Variables of Particleboard Construction Along with Response Surface Method Codes

Variables		Levels	
	Low Limit (-1)	Medium Limit (0)	High Limit (+1)
Density (g/cm^3)	65	70	75
Adhesive (%)	8	9.5	11
Slenderness ratio	13	30	47

The wood chips were manually glued together using a pistol (a pneumatic spray gun for manual use). The laboratory particleboards were then manufactured using a hot hydraulic press (Hydraulic press, Esfahan, Iran) in dimensions of 40 cm × 40 cm and three density levels (0.65, 0.7, and 0.75 g / cm^3), three adhesive percentage levels (8, 9.5, and 11%), and three slenderness ratio levels (13, 30, and 47). In this research, other influential factors in particleboard manufacturing were held constant. After being removed from the press, the boards were stored in an air conditioning chamber (relative humidity 65% and temperature 20 °C) for two weeks to balance the moisture. The MOR and MOE test samples were prepared in accordance with EN 310 (1993), while IB test samples were prepared in accordance with EN 319 (1993). The mechanical characteristics of the particleboard were tested using a Hounsfield testing machine (25 k S UK).

Analysis of Variance and Mathematical Model

Following the design selection, the model equations and coefficients were developed. The response surface approach uses the equation of the complete quadratic model or its simplified version. The quadratic model is written as follows (Eq. 1 and 2):

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_i + \sum_{j=1}^{k} \beta_{jj} x_i^2 + \sum \sum_{i<j=2}^{k} \beta_{ij} x_i x_j \qquad (1)$$

$$y = X\beta + \varepsilon \qquad \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} = \begin{bmatrix} 1\ x_{11}\ x_{12} \ldots x_{1k} \\ 1\ x_{21}\ x_{22} \ldots x_{2k} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ 1\ x_{n1}\ x_{n2} \ldots x_{nk} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ . \\ . \\ . \\ \beta_k \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ . \\ \varepsilon_n \end{bmatrix} \qquad (2)$$

The least-squares approach was used to solve the preceding system of equations, and the coefficients of the solution were obtained. The solution was anticipated after finding the coefficients using the preceding equations. The model's agreement with the experimental results should subsequently be verified. Several approaches to this include residual analysis, a departure from projected criteria, and the mismatch test. The coefficient of determination (R^2) expresses the model's overall predictability, and Fisher's exact test determines its statistical significance (F-Value). A t-test was also used to calculate regression coefficients (model). However, because it represents variations in the mean response, R^2 alone cannot assess the model's correctness. As a result, another coefficient known as the adjusted coefficient of explanation (R^2_{adj}) was used. Unlike R^2, the average sum of squares is utilized in this coefficient rather than the sum of squares. Equations 3 and 4 provide the procedure for computing these two coefficients,

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \qquad (3)$$

$$R^2_{adj} = 1 - \frac{SS_{residual} / DF_{residual}}{SS_{total} / (DF_{model} + DF_{residual})} \qquad (4)$$

where $SS_{residual}$ is the sum of the remaining squares, DF is the degree of freedom, and SS_{total} is the sum of the total squares ($SS_{residual} + SS_{model}$).

RESULTS AND DISCUSSION

The lowest P-value defines the best model in the response surface method, the highest value of the coefficient of determination (R^2), and the adjusted coefficient of determination (R^2_{adj}). Table 2 shows the data for the suggested response surface method models (linear model, interaction model, complete quadratic model, and tertiary model). Accordingly, the criteria for choosing the suggested model of the response surface method were based on the fitting weakness' lowest and maximum p-values, as well as the adjusted overall explanation coefficient. As a result, the Linear model, Quadratic model, Interaction, (2FI), and Cubic equation were presented as models for MOR, MOE, and IB, respectively. The lack of fit was negligible in this investigation based on the analyzed features, suggesting a satisfactory model fit.

Table 2. Proposed Models of Response Surface Method

Mechanical Properties	Model	P-value	Lack of fit P-value	R^2 Adj.	R^2 Pred.	Process Order
MOR	Linear	< 0.0001	0.9248	0.9011	0.8909	Proposed
	Interaction	0.7872	0.8658	0.8898	0.8693	
	Quadratic	0.5221	0.8677	0.8852	0.8422	
	cubic equation	0.7603	0.7768	0.8626	0.2699	Aliased
MOE	Linear	< 0.0001	0.0988	0.7758	0.6942	
	Interaction	0.4759	0.0845	0.7752	0.4115	
	Quadratic	0.0017	0.8641	0.9105	0.8747	Proposed
	Cubic equation	0.7992	0.6073	0.8906	-0.7665	Aliased
IB	Linear	< 0.0001	0.2366	0.8852	0.8192	
	Interaction	0.0031	0.8761	0.9412	0.9379	Proposed
	Quadratic	0.6136	0.8399	0.9368	0.9233	
	Cubic equation	0.9547	0.2802	0.9144	-4.6132	Aliased

Table 3 shows the results of analyzing the suggested response surface method model for each dependent parameter (MOR, MOE, and IB). The values of the coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), and the predicted coefficient of determination (R^2*pred*) for the linear model suggested by the response surface method were for MOR: 0.91, 0.90, and 0.89, for MOE 0.94, 0.91, and 0.87, and for IB 0.95, 0.94, and 0.93, respectively.

Table 3. Analysis of Variance (ANOVA) for Proposed Models of Response Surface Methodology

Variables	p-value	F	DF	p-value	F	DF	p-value	F	DF
Model	*0.0001	59.74	6	*0.0001	67.78	3	*0.0001	25.88	9
(D) Density	*0.0001	258.22	1	*0.0001	143.12	1	*0.0001	96.08	1
(A) Adhesive	*0.0001	42.54	1	*0.0001	21.67	1	*0.0001	34.15	1
Slender(S) ness ratio	*0.0001	36.58	1	*0.0001	38.55	1	*0.0001	68.09	1
D*A	0.0102	8.46	1	-----	-----	-----	0.0324.	5.73	1
D*S	0.0041	11.17	1	-----	-----	-----	0.6052	0.28	1
A*S	-----	-----	-----	-----	-----	-----	0.0013	16.64	1
Residuals	-----	-----	16	----	----	19	----	----	13
Lack of fit	0.8761 ns	0.4252	8	0.92 ns	0.39	11	0.86 ns	0.35	5
Pure error			8	----	----	8	----	----	8

* Significance at the level of 5%; ns: lack of significance; df: degree of freedom; MS: Average squares; P-value or Sig; Significance

The difference of 0.01 between the R^2 value and the R^2_{adj} value for the MOR values, 0.03 for the MOE, and 0.01 for the IB show that the suggested model has a good agreement with the response surface method (very excellent agreement 0.2). For all three models, the lack of fit became irrelevant. The fit's weakness alters the results around the adapted model, allowing the accuracy of the adaptive model to be measured. The mismatch becomes important if the model does not match the results. Table 3 also includes the variance analysis of the suggested model of response surface method for MOR, MOE, and IB. Except for the interaction of adhesive % and particle size on MOR, the independent and interaction effects of particleboard density, adhesive content, and slenderness ratio on MOR, MOE, and IB were statistically significant. Increased density boosted the extent of compaction, which increased the contact surface between particles in the particleboard. The particleboard with the highest density (0.75 g / cm^3) and the maximum quantity of adhesive (11 %) had the highest mechanical strength values (MOR = 23.17, MOE = 2.941, and IB = 0.55). Liao *et al.* (2016), Cosereanu and Cebu (2019), and Valle *et al.* (2020) similarly demonstrated a direct influence of increasing density and adhesive quantity on particleboard mechanical qualities. In addition to the non-fit, the model was evaluated through a graph of predicted and actual values (Fig. 1).

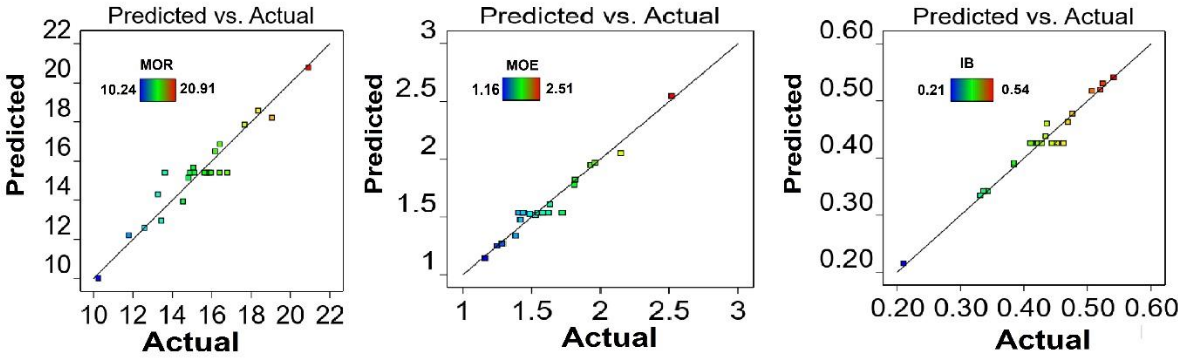

Fig. 1. Matching between the actual data input to the software and predicted by the RSM

All points associated with the actual and anticipated outcomes were put on or near the 45° line, reflecting the model's suitable reaction to the findings. This graph also depicts the relationship between the experimental and predicted outcomes using the Response surface method. Figure 2 show three-dimensional graphs showing changes in MOR, MOE, and IB when density values and adhesive quantities were at 13, 30, and 47.

Figure 2 depicts the MOR, MOE, and IB values of the particleboard samples in the slenderness ratios of 13, 30, and 47 with variation of density and adhesive quantity. The values of MOR and MOE rose as the density, adhesion, and elongation factors increased (diagrams a through f). However, when the slenderness ratio increased (along with the quantity of adhesive and density), the value of IB declined (g through i diagrams). The final MOR, MOE, and IB prediction model in terms of the significant relevant elements are shown in Eqs. 5 through 7:

$$\text{MOR} = -33.592 + (56.38D) + (0.731333A) + (0.0860588S) \tag{5}$$

$$\text{MOE} = 44.5181 + (-131.878D) + (0.159485A) + (0.023490\,S) + (1.04783\,DA) + (0.020456 \times DS) + (0.001519\,AS) + (90.76107D^2) - (0.043377 \times A^2) + (0.000150 \times S^2) \tag{6}$$

$$IB = -2.05645 + (3.42133D) + (0.188282A) + (-0.0224108S) + (-0.246667DA) + (0.025DS) + (0.000303922AS) \quad (7)$$

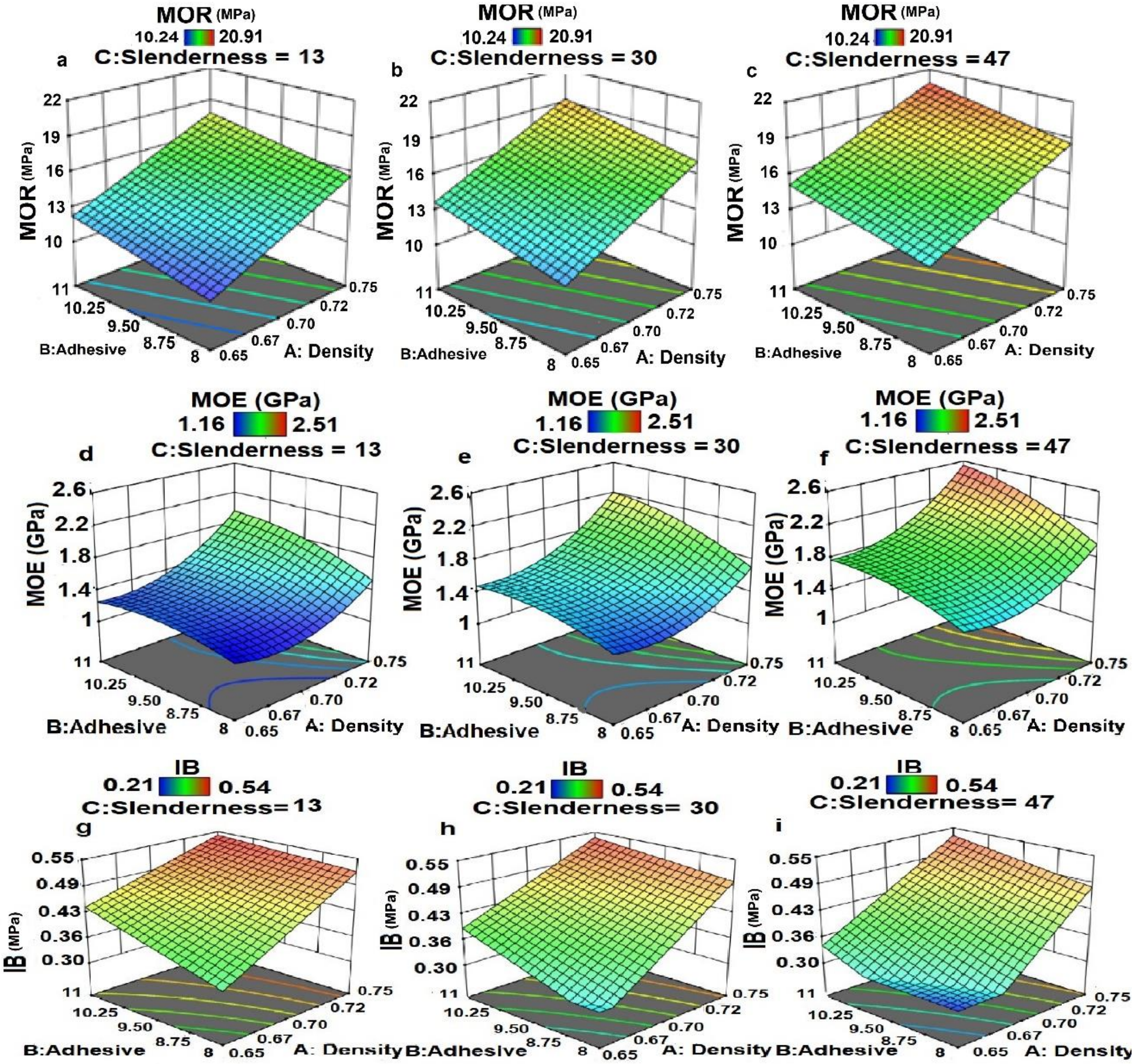

Fig. 2. 3D depiction showing changes in MOR, MOE, and IB based on adhesive and density changes for slenderness ratios of 30, 13, and 47 (Density = g/cm^3, Adhesive = %, Slenderness Ratio = Dimensionless, MoR = MPa, MOE = GPa, and IB = MPa).

The ultimate value of the examined properties (MOR, MOE, and IB) at the levels of the variables tested in this study is shown in Eqs. 5 through 7. With the precision of R^2 and R^2_{adj}, the ultimate value of the resistance in the range of the independent variable may be anticipated using these relationships. It is also feasible to assess the efficiency of each variable by looking at other relevant variables in the desired qualities, and lastly, to create a more accurate forecasting model by combining all of the contributing variables.

The level optimizer part of Design-Expert software was used to accomplish the multi-response optimization procedure. Derringer's utility performance maximized the three MOR, MOE, and IB responses simultaneously. The EN 312-3 (1993) standard of ordinary particleboard requirements for dry furniture usage in the nominal thickness range of 13 to 20 mm, for MPa 11 = MOR, MPa = 1600 = MOE, and MPa = 0.35 MPa. Multi-response optimization was performed in three modes, according to this standard. The criteria for reaching the required response were evaluated in the first scenario using the numbers specified in the standard. That is, the objective was calculated based on EN 312-3 (1993) as the lowest level of acceptable resistance. In the scenario, the fluctuating density and the quantity of adhesive used raise the expenses. Furthermore, when they consume more glue, they will produce more formaldehyde gas, thereby increasing the hazards to health. The final choice was chosen in the independent variables for these two variables, and the slenderness ratio variable with the range mode utilized in the test was chosen. This was done in such a manner that by varying the slenderness ratio, density, and percentage of adhesive, an acceptable response in terms of the standard could be obtained. Through managing particle size while making particleboard, the desired outcome may be accomplished with the least number of resources, which is important from both an economic and environmental standpoint. In the third scenario, it was considered that given the range of variables analyzed, how can the highest resistances be attained to diversify the product's application range? In this scenario, the variables were in test range mode. The goal function was set to maximum to get the best possible response regarding the range of variables under investigation. Table 4 shows the optimization functions for the variables.

Table 4. Objective Functions for Optimization

Objective Functions	Density (g/cm^3)	Adhesive (%)	Slenderness Ratio	MOR (MPa)	MOE (GPa)	IB (MPa)
Standard condition						
First objective function (minimum standard requirements)	-----	-----	-----	11	1.6	0.35
Second objective function (Minimum density and adhesive (%) in the range of slenderness ratio changes)	At least (0.65-0.75)	At least (8 to 11)	The range of slenderness ratio changes (13 to 47)	-----	-----	-----
Third objective function (maximum resistance)	-----	-----	-----	Maximum	Maximum	Maximum

Table 5 shows the outcomes in terms of attaining the minimum acceptable standard, the minimal density and quantity of adhesive used, and the difference between these values and the actual values.

In this optimization approach, the elements with a favorable influence on profitability were increased, while those with a negative impact were eliminated. Consequently, goal functions and restrictions were developed to optimize unit profitability. In actuality, the objective of this research was not to maximize a target function in Rials but to maximize the unit's profitability by concurrently maximizing and decreasing positive and negative aspects.

As mentioned, the objective of the response surface approach is to identify the key elements that will produce the highest response. Each goal function was defined in this procedure by picking elements at their maximum, minimum, or particular values.

The first function displays the performance index necessary to achieve the minimum resistance specified by EN 312-3 (1993). In this scenario, the goals of MOR = 11 MPa, MOE= 1.60 MPa, and IB = 0.35 MPa were used to calculate the values of the independent variables necessary to achieve the required response. In this part, the greatest performance level (0.89) was offered as the initial solution for the optimization strategy with the specified constraints. To achieve these strength and modulus goals, the density was optimized at 0.65 g/cm^3, the adhesive content was 10.4%, and the slenderness ratio was 36.6.

The second function displays the performance index for minimizing the consumption of raw materials while achieving the minimum resistances specified by the EN-312-3 (1993) standard. The quantity of density, the amount of adhesive, and the amount of slenderness ratio utilized in the lowest state were chosen. The standard's requirements established the intended responses. This strategy showed that to achieve the minimum mechanical strengths specified by the EN-312-3 (1993) standard while using the least amount of raw materials, a density of 0.68 g/cm^3, an adhesive content of 9%, and slenderness ratio of 42.7 units were necessary. This section showed the highest yield with a value of 0.781%. Comparing these two methods reveals that the primary difference between them was that the second method required 1.44% less adhesive, had a greater density of 0.04, and had a higher slenderness ratio of 6.06 than the first method. Given that adhesive consumption is one of the most important aspects of manufacturing in terms of cost and that lowering adhesive consumption in terms of the environment is desired, the second technique is expected to be more suitable given the distinctions mentioned above.

In the third method, the greatest recorded strength and modulus levels were found in the maximum values of independent variables such as density of 0.75 g/cm^2, adhesive content of 11%, and slenderness ratio of 47, with MOR = 20.78, MOE = 2.54, and IB = 539/0. In addition, after improving the examined factors and expected outcomes, particleboard was manufactured using the improved variables, and its resistances were compared to the predicted values.

Table 5 reveals that all actual values were greater than the projected optimization approach. The difference between predicted and actual values demonstrates that the optimization approach is suitable for laboratory and industry research, but not for exact predictions.

Table 5. Optimization Outcomes vs. Standard Values

Variables and Mechanical Properties		First Objective Function	Second Objective Function	Third Objective Function	Standard Condition
Variables	Slenderness Ratio	37.15	45.99	47	----
	Adhesive(%)	10.54	8.09	11	----
	Density (g/cm3)	0.65	0.69	0.75	----
Mechanical Properties	MOE (GPa) Actual	1.74	1.82	2.83	----
	MOE (GPa) Predicted	1.60	1.60	2.54	1.60
	MOR (MPa) Actual	14.4	15.05	21.31	----
	MOR (MPa) Predicted	13.96	15.68	20.78	11
	IB (MPa) Actual	0.37	0.43	0.60	----
	IB (MPa) Predicted	0.35	0.35	0.54	0.35
Desirability Index		0.89	0.81	0.98	----

Particle size and shape are crucial parameters that affect the quality and utilization properties of particleboard. Shanthi *et al.* (2014) reported that there are many techniques available to measure particle size distribution, such as sieving. The existing methods involve handling of the material physically or electromagnetically, and these methods are quite often offline and time consuming. Moreover, digital image processing has been established based on considering a single parameter of the particle profile. Such methods can be used as an alternative in the wood-based panel industry. Their functionality has been enhanced significantly during the past years, and they can provide information about particle length, width, and slenderness ratio; in addition, the measuring procedure has become much faster (Shanthi *et al.* 2014; Benthien *et al.* 2018). Also, Chaloupková *et al.* (2018) reported that the photo-optical analysis based on image processing is fast, and it provided extensive and more precise results. However, the possibility of separation of particle size fractions is missing and the measuring range is limited. Therefore, based on the new methods, the measurement of slenderness ratio has the potential to be practical and it can be helpful for improving the material efficiency of wood particles to reduce the amount of wood used for panel. To date, technology has been lacking to determine changes in particle size composition. Using the image analysis processing method and 3D digital image analysis are very useful methods for measuring the wood particle dimension and also for studying the mechanism of particle gluing for improving the quality of particleboard (Shanthi *et al.* 2014; Chaloupková *et al.* 2018; Benthien *et al.* 2022).

CONCLUSIONS

1. The production conditions of particleboard were optimized to reduce the consumption of raw materials and the percentage of resin while obtaining the standard conditions of particleboard properties based on the EN-312-3 (1993) standard, due to the acceptable accuracy of the response surface method models. The optimized quantities of density, percentage of adhesive, and slenderness ratio were 0.65 g/cm^3, 10.54%, and 37.15, respectively,
2. To meet the minimum mechanical strengths required by EN312-3 (1993), the findings revealed that by lowering the quantity of glue used by 8.09%, raising the density to 0.69 g/cm^3 unit, and increasing the slenderness ratio from 37.15 to 46.99, particleboard with greater strengths than the standard permitted value could be produced.
3. Changing the slenderness ratio is a key component in mechanical resistance control. The quantity of glue used and the density of the board may both be lowered by selecting the right amount of slenderness ratio.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mohammad Arabi, Akbar Rostampour Haftkhani, and Reza Pourbaba. The first draft of the manuscript was written by Mohammad Arabi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Author Statements

The authors certify that they have participated sufficiently in the work to take public responsibility for the content. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the *BioResources* journal.

Data Availability Statements

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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