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Research Article

Experimental Investigation of Sorghum Stalk and Sugarcane Bagasse Hybrid Composite for Particleboard

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This study evaluated the physical-mechanical properties of three-layer particleboard made from sorghum stalk and sugarcane bagasse hybrid reinforced bonded with urea-formaldehyde resin. The production of particleboards using the sorghum and bagasse particles has been established at the ratio of (25 : 50 : 75) sorghum stalk and sugarcane bagasse with urea-formaldehyde as a matrix at different concentrations (50 kg/m^3, 60 kg/m^3, and 70 kg/m^3) and pressing pressure (18 MPa, 20 MPa, and 22 MPa) through hand mixing from 3 to 5 minutes and then hot press within a temperature range of 160°C to 180°C for 4 minutes. The particleboards were produced with their proportions through the Taguchi design of the experiment (L_9) approach. The experimental results were analyzed using Taguchi design and ANOVA with a general linear model. The experimental results showed that internal bonding, flexural strength, modulus of elasticity, and moisture content were significantly improved with high resin content and pressing pressure from 18 MPa to 22 MPa. The thickness swelling value also dropped where the resin concentration varies from 50 kg/m^3 to 70 kg/m^3 and shows better board stability. In contrast, the water absorption increased as resin content was increased. Results from ANOVA provide that SS3B1P3UFR3 (3 : 1 ratio of Sorghum with bagasse, 22 MPa of pressing load, and 70 kg/m^3 urea-formaldehyde concentration) is the most optimal combination of variables for the better performance of particleboard.

1. Introduction

Particleboard is one of the most common wood-based composite materials produced from lignocellulose materials in the form of discontinued discrete particles blended with a suitable binder under the application of heat and pressure. It is used for household and office materials because of its desirable properties like low density, sound absorption, and excellent machining properties by Senthil Kumaran et al. [1–3]. It is categorized into three based on the density of fiber particles: (A) low-density fiberboard, (B) medium-density fiberboard, and (C) high-density fiberboard. Particleboard is produced in densities ranging from around 590 kilograms per cubic meter (kg/m^3) to 800 kg/m^3. Fong et al. [4] showed that sorghum is considered one of the most common endemic multipurpose crops used as a source of energy for rural communities, food, feed for their animals (stalk), and alcoholic and nonalcoholic beverages. Nowadays, sorghum is the third vital crop in area coverage and production and is becoming the second in “injera” making after “tef” in Ethiopia. Gebretsadik et al. [5] investigated that the regional distribution of sorghum production is highly accounted for by the Amhara and Oromia regions, nearly 80 percent of total production. Sugarcane bagasse is the fibrous residue remaining after the sugarcane stalk has been crushed and the juice was removed as stated by Nagieb et al. [6]. Han et al. [7] stated that, in addition to its form versatility, bagasse can be accessed in the entire world in sufficient amounts, and the processing cost for manufacturing its composite (particleboard) is very reasonable. Ethiopia is one of the tropical countries which can produce sugarcane widely. According to the Ethiopian sugar corporation, statistical data shows that nowadays, from 200,000 to 250,000 hectares of land would be covered by sugarcane. On average, one hectare of sugarcane generates up to 10 tons of waste (Loh et al. [8]). Moreover, from 10 tons of sugarcane, nearly 3 tons of bagasse would be produced in the milling process discussed by Carvalho et al. [9]. The sugarcane industry in Ethiopia has increased the total daily crushing capacity from 20.000 tons of cane per day to more than 220.000 tons per day. However, it still did not use bagasse to produce particleboard on an industrial scale in Ethiopia. Up to date, bagasse is a source of energy in the sugarcane industry. However, the efficiency of bagasse for energy production (calorific value) is relatively low (discussed in Riza Wirawan et al. 2011 [10] and Flores et al. 2011 [11]). This condition was the driving force behind the need for enhancing the economic value of sugarcane bagasse. Natural fiber composite is a material that can be reinforced by fibers extracted from plants and animals [12]. Natural fiber composite (NFC) has many advantages over synthetic fiber-reinforced composite (SFC). It has a low density and low production cost and is biodegradable since it is derived from renewable resources and good thermal and acoustic insulation. Those relative advantages over SFCs would be emphasized when developing new products from NFCs [13].

All particleboard factories in Ethiopia have used eucalyptus globules as raw material for particleboard production. This lonesome reinforced material leads to the country's scarce resources, and using eucalyptus exposes the environment to deforestation. This research introduces a composite material made from sorghum stalk and sugarcane bagasse used to produce particleboard. It also aimed to replace eucalyptus globules via sorghum stalk and bagasse to ensure sustainable resource supply. Moreover, the utilization of those potential candidate raw materials gives economic value to society (Muthukumaran et al. [14]).

The primary goal of this research is to use potential waste to increase the economic value of waste in Ethiopia, as it can sometimes provide income opportunities for farmers by supplying sorghum stalks to firms. Sugar manufacturing industries profit from bagasse supply because they use only an average of 11% of their waste (bagasse) as an energy source in Ethiopia.

Furthermore, when particleboard manufacturing industries use waste resources (sorghum stalk and bagasse), they will reduce their production costs by reducing the starting process by using a large chopper machine to chop eucalyptus in the particle preparation stage. This chopper machine requires a large amount of electric power, whereas, unlike eucalyptus, sorghum stalk does not require this chopper machine and can be chopped by a small machine. On the other hand, bagasse does not require chopping and is directly fed into a flaker machine. (This statement implies that when industries use sorghum stalk and bagasse, they will reduce production costs and gain a cost advantage.)

The hypothesis for combining two materials is to improve particleboard performance by improving mechanical properties such as modulus of rupture and modulus of elasticity. By definition, bagasse flake has a long and cylindrical fabric. It is used to form a strong interfacial bond with the number of discrete sorghum stalk particles, which produces long-chained cellulose. Because the larger surface area of the particle should result in better stress distributions than shorter particles, this longer and thinner particle produces a board with high bending strength and good board stiffness.

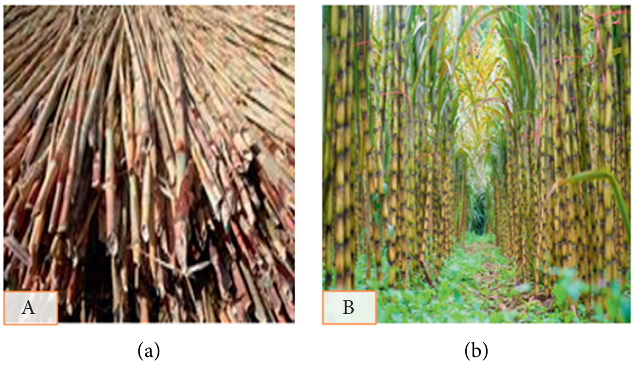
2. Materials and Method

2.1. Materials. The following materials will be used for the production of particleboard from sorghum and bagasse. Sorghum stalk and bagasse were crushed to different particle sizes and geometry, as required for the three-layer particleboard. The particle size was categorized into two different levels: core layer flake (0.5 to 1.5 mm) and surface layer flake (1.5 mm to 2.5 mm), and it was measured during screening with the standard mechanical sieve.

2.2. Reinforcement Materials. Sorghum and sugarcane residues (stalks) were used in this study as lignocellulose raw materials to manufacture three-layer bonded particleboard panels. They are easily accessible, and low purchasing costs and their desirable properties are shown in Figure 1.

2.3. Matrix Materials/Binding Agent. Urea-formaldehyde resin (UFR) is used as a binding agent. UFR is the most common thermosetting resin, usually referred to as amino resins. It is commonly used as an adhesive by the forest product industries due to its desirable properties [15]. It is white in color and has a density from 1.26 to 1.27 g/cm^3, viscosity of 300–500 cps at room temperature, pH value of 7.5–8.2, gel point (100°C, sec) of 25 to 30, and 65% solid content [11]. UFR has numerous applications in the wood-based composite like fiberboard and particleboard industry. Besides its economy, it has many advantages such as good performance; it has adequate strength to fulfill the required standards, good solubility in water, fast curing time as thermoplastic, excellent curing reaction in the hot press, and excellent thermal properties [16]. However, UFR has also had several drawbacks, such as low resistance to water, and it affects human health, particularly in the indoor environment due to its emission from the boards [17].

2.4. Other Additive Materials. Hardeners are also called curing agents, accelerators, or catalysts added to the resin conducted by Nagieb et al. [6]. Harshavardhan and Muruganandam [18] stated that hardness was to facilitate the curing process during board manufacturing by accelerating the moisture dispels. Ammonium salt is a more widely used hardener because it is cheap and convenient to handle and gives a high rate of pot-life to setting time (Bolboacă and Jäntschi [19]). The most commonly used ammonium salts



(a) (b)

Figure 1: Raw material for reinforcement: (a) sorghum stalk and (b) sugarcane bagasse.

are ammonium chloride (NH4Cl). Paraffin wax is an inexpensive thermoplastic used as an emulsion agent for shining and thickness swelling. It is the most commonly used commercial emulsion oil due to its large latent heat, environmental harmlessness, unpleasant odor, nontoxicity, and low price. In addition, it is added to the surface layers to protect against accidental water spillage.

2.5. Methods. Developing particleboard from sorghum and bagasse with UFR and analyzing its physical-mechanical properties involve different operations. However, the following procedures were carried out by Hrázsk and Král [20].

2.6. Board Manufacturing. The overall stapes used for board manufacturing started from particle preparation, including drying and screening, blending particles with UFR and its necessary additives, mat-forming, board pressing, and trimming. A total of 27 sample boards were manufactured with their respective factor combined with the dimension of 300 mm × 300 mm X10 mm. The ratio between SS and SB was fixed as 25 : 50 : 75 where SS represents sorghum stalk and SB represents sugarcane bagasse. The particles were blended with UFR concentration variations of 50 m^3/kg, 60 m^3/kg, and 70 m^3/kg and the other additive chemicals with a low-speed stirrer. After blending, the particles were scattered layer by layer manually in a mold before being pressed at a given pressing a load of 18 MPa, 20 MPa, and 22 MPa with a temperature of 160 to 180°C for a 4-minute press close time.

2.7. Design of Experiment (DoE). In this study, a Taguchi method with an L9 orthogonal array of the statistical DoE technique was carried out to analyze and optimize the process parameters over physical-mechanical properties listed in Table 1. The Taguchi method reduces the variance of experiments by finding the optimum setting parameters reducing the number of trials, cost, and time. It is a simple, systematic, reliable, and more efficient technique for optimizing the variance using a small number of experiments discussed by Senthil Kumaran et al. [1].

The experiment has four variables (%wt. Sorghum stalk, %wt. Sugarcane bagasse, pressing load, and UFR concentration) at three different levels (lower, medium, and higher). However, a Taguchi experiment with an L9 (3^4) orthogonal array would be conducted (9 tests, 4 variables, 3 levels) with three trials listed in Table 2.

Table 1: Control variables and their levels.

S.no	Variables	Level (ratio)		
		Level I	Level II	Level III
1	% wt. Sorghum	1	2	3
2	% wt. Bagasse	1	2	3
3	Pressure (MPa)	18	20	22
4	UFR concentration (kg/m^3)	50	60	70

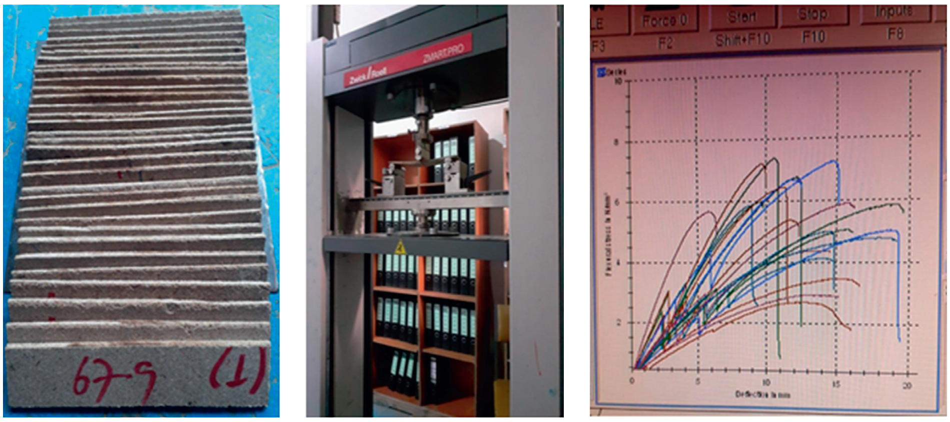
Based on the Taguchi design of experiments L_9 (3^4) approach, the experiments were performed on particleboard with a particle size of 0.5 to 1.5 mm for the surface layer having 2 mm thickness for each side and 1.5 to 2.5 mm for the core layer with 4 mm thickness. The effect of the control factors on the mechanical parameters such as modulus of rupture (MOR), modulus of elasticity (MOE), internal bonding (IB), and physical properties, particularly board moisture content (MC), density (BD), water absorption (WA), and thickness swelling (TS), was found using their respective procedures as discussed by Anwar et al. [21]. Through analysis of variance (ANOVA) calculations, each control factor's contribution influencing the above-measured parameter shows the optimal parameter combination of the process.

2.8. Modulus of Rupture (MOR). Modules of rupture, also known as flexural strength, are mechanical properties of materials. The stress in a material just before a flexural failure is shown in Figure 2. It was determined by applying a load to the center of a specimen supported at the two ends with a strain rate of 0.067 per second. Accordingly, the specimen preparation and test procedure were carried out (EN 310 1993). The test specimen was prepared based on the (EN 310 1993) standard with a dimension of 250 mm × 50 mm × 8 mm. Each specimen's width, length, and thickness shall be measured to an accuracy of not less than 0.03%.

The flexural strength of the board was calculated by determining the ratio of the bending moment for the

Table 2: Taguchi orthogonal array design.

Sl. no	C1	C2	C3	C4
1	1	1	180	50
2	1	2	200	60
3	1	3	220	70
4	2	1	200	70
5	2	2	220	50
6	2	3	180	60
7	3	1	220	60
8	3	2	180	70
9	3	3	200	50



(a)

(b)

(c)

Figure 2: Test procedure and graph for flexural strength.

maximum load F_{max} at the given cross-section using the following equation:

$$\text{MOR} = \frac{3 \times F_{\text{max}} \times L}{2 \times b \times t^2}, \quad (1)$$

where F_{max} is the maximum load (N), b is the width of the specimen (mm), t is the thickness, and L is the span in mm.

2.9. Modulus of Elasticity (MOE). A modulus of elasticity is a mechanical property of particleboard in static bending tests that measures the resistance to bending related to the stiffness of the sample specimen (Khazaeian et al. [22]).

2.10. Internal Bonding (IB). The internal bonding strength (tensile strength perpendicular to the surface of particleboard) indicates the resistance of a board to splitting or delamination as shown in Figure 3. Squared test specimens (doing the test with a side length of 50 mm) were glued to metal loading blocks (EN 310 1993). The test was done by placing the glued test sample on the test machine and anchored on both sides. The specimens were subjected to a tensile force perpendicular to the particleboard surface until rupture occurred with the uniform rate of motion (strain rate), 0.068 per second. The aim of determining the internal bonding strength of the particleboard is to investigate the correlation between the discrete fiber particles on the board.

The universal testing machine gradually pumped the anchored sample board with the indicated strain rate; both tensioned sides were stretched till it failed, and the failure occurred by splitting each side. Mathematically, the internal bonding of particleboard can be calculated by

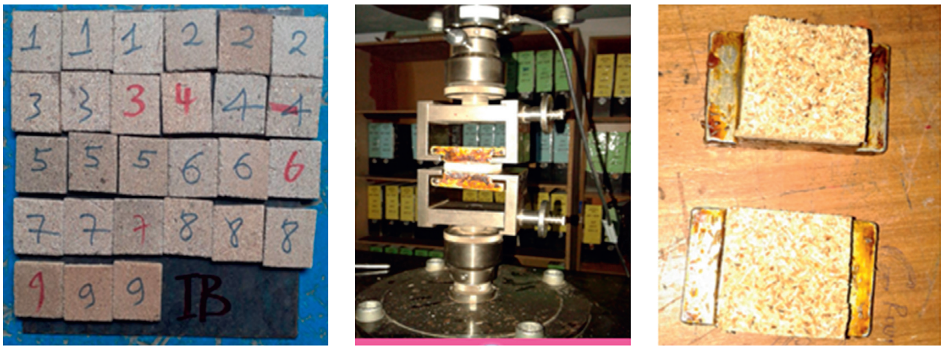
$$\text{Internal Bonding Strength} = \frac{\text{Maximum Applied Load}\,(N)}{\text{Area of Specimen}\left(mm^2\right)}. \quad (2)$$

2.11. Board Density Test (BD). The composite material has two principal phases, namely, reinforcement and matrix. The actual board density can be determined through experimentally measurement by a simple water-immersion technique, while the theoretical density of the composite can be calculated by empirical formula as [23]

$$\rho_{\text{com}} = \frac{Mb}{Vb}, \quad (3)$$

where ρ_{com} is the theoretical density of the composite, and M_b and V_b are the mass and volume of the sample board, respectively.

In the production process, the air gets trapped, which forms a void. The volume fraction of voids or free-gap (Vf) in the composites is determined by using the following equation [24]:



(a) (b) (c)

Figure 3: Internal bonding strength testing process.

$$\mathrm{Vf} = \frac{\rho_{\mathrm{th}} - \rho_{\mathrm{ac}}}{\rho_{\mathrm{ac}}}, \tag{4}$$

where V_f is the volume fraction of voids, and ρ_{th} and ρ_{ac} represent the theoretical and actual density of the sample board.

Test specimens were prepared by JIS A 5908 : 2003 and nine sample specimens (three repetitions) with the dimension of 50 mm × 50 mm × 8 mm.

2.12. Moisture Content (MC). Most wood-based products show dimensional instability due to environmental factors. Like other wood-based products, particleboard will respond to the change in dimension due to environmental conditions like humidity. The change in dimension of the board would be due to the change in moisture content. The moisture could be determined in the stage flake and moisture up taken by the raw board. The moisture content of the flake can be measured using an electric moisture meter and it should not exceed 5%.

In contrast, the amount of moisture on the board could be determined using the weighting and drying of the specimen inside the oven, called the oven-dry test. Oven-dry testing is a technique used to determine the amount of moisture inside the particleboard by the weight loss through drying in the oven with a temperature range of 100°C to 105°C for a duration of 16 hrs. Mathematically, it is calculated as

$$\text{Raw Board } MC\,(\%) = \frac{\text{Mass in} - \text{Mass out}}{\text{Mass out}} \times 100\%. \tag{5}$$

2.13. Specimen Preparation. Nine test specimens with three trials and the dimension of the specimen of 50 mm × 50 mm × 8 mm would be prepared accordingly to ASTM standards as shown in Figure 4. A vertical wood saw is used for striping the test specimen as required.

2.14. Water Absorption Test. This test is used to determine the amount of water absorbed under certain environmental conditions. The results imply the performance of particleboard in a humidifying environment, especially for outdoor service. The test was conducted in two ways. The specimen was immersed in a distal water tank for 24 hours and then weighted and recorded their mass (JIS A 5908 : 2003). The test procedure was defined as follows. The test specimens were dried in the oven at a temperature of 110°C to 120°C for 1 hour, and the dry weight for each sample was recorded. After cooling the specimen and attaining it at room temperature, each test specimen should be weighed and its dried weight was recorded (water-free weight). Next, the specimens were immersed entirely in a tank filled with distal water at room temperature for 24 hrs. Now measure the weight of the wetted specimen after removal from the tank. Finally, the amount of water absorbed by the board would be determined using the following mathematical equation:

$$\text{Water Absorption after 24 Hours}\,(\%) = \frac{\text{Wet weight}\,(24\text{hr}) - \text{Dry weight}}{\text{Dry weight}}\,\mathrm{X}100\%. \tag{6}$$

2.15. Specimen Preparation. According to the JIS A 5908 : 2003 standard for water absorption test, each specimen was prepared with a 25 mm × 25 mm × 8 mm dimension as shown in Figure 5.

2.16. Thickness Swelling Test. Thickness swelling or change in dimension is the response of particleboard where it is imposed for the socking of water. Therefore, it is used to analyze the swelling behavior of particleboards due to the

Figure 4: Boards for moisture content testing.

(a) (b)

Figure 5: Water absorption testing.

soaking of water. Like water absorption, it is also determined by measuring the increment in the thickness of the test specimen within 24 hrs of immersion in water. To determine the dimensional instability or thickness swelling after immersion in water at room temperature (21°C) with pH 7 (distal water) for 24 hours of the particleboard carried out following the ASTM standard, thickness swelling for 24 hours was calculated as

$$\text{Thickness swelling within 24 hrs. } (\%) = \frac{\text{T2 (24 hrs.)} - \text{T1}}{\text{T1}} \text{X100}. \tag{7}$$

2.17. Microstructure Test. The main objective of microstructure tests for particleboard was to observe the distribution of adhesive (UFR) within a particle and its effect on the characteristics of the board. The test was conducted by using an optical microscope. Sarmin et al. [25] presented the principle of optical microscopy which is to shine a light through (transmitted) or onto the surface (reflected) of a specimen and inspect it under magnification with 10X magnification power. The specimens for the microstructure test consisted of particleboard with a carefully polished cross section. The size of the board was cut into a 25 mm by 25 mm rectangular flat piece. After blanking the sample with 25 mm × 25 mm × 8 mm, we remove the levels and clean the specimen's surface with fine sandpaper.

3. Results and Discussion

3.1. S/N Ratio Determination. According to Taguchi, the approach's signal-to-noise ratio represents the value's desire and not desirable characteristics. The S/N ratio can be determined by the mean to square deviation ratio discussed in Xiao et al. [26]. From the ANOVA results, the higher observed value shows the better performance of particleboard in the case of IB, MOR, MOE, and BD and it is called "higher the better." But the lower observed value represents the better performance of particleboard, such as MC, WA, and TS, which are called "lower the better" characteristics. Therefore, IB, MOR, MOE, and BD loss functions were "larger is better". Because the large value of the parameter shows the more strong particleboard, the lower WA and TS and the board's best performance and the lower loss function were better. It implies lower water absorption, lower dimension, board mass change, and lower spring back of the board listed in Table 3.

3.2. Internal Bonding Strength. The results of IB from Table 3 ranged from 0.39 to 1.13 N/mm^2. The minimal requirements (JIS A 5908 : 2003) of IB strength for general purpose boards are 0.15 N/mm^2. According to the test results, all boards had the required level strength of IB for general purposes.

Table 4 shows the ranks of variables based on delta value, which compares based on the relative magnitude of effects. The delta value is the highest average effect minus the lowest average effect for each factor. For example, the response S/N

Table 3: Summary of experimental results for various conditions.

Run	Input parameters				Output response					
	%wt. Sorghum	%wt. Bagasse	Pressing load (bar)	UFR (kg/m^3)	IB (MPa)	MOR (MPa)	MOE (GPa)	MC (%)	WA (%)	TS (%)
1	1	1	180	50	0.62	4.84	4.02	9.21	61.09	38.98
2	1	2	200	60	0.75	6.08	12.7	7.66	65.24	39.02
3	1	3	220	70	1.09	7.13	7.72	6.99	55.62	30.99
4	2	1	200	70	1.13	8.79	10.1	8.67	50.31	32.94
5	2	2	220	50	0.8	4.82	5.06	4.39	52.23	37.53
6	2	3	180	60	0.91	6.19	7.58	4.73	52.85	39.54
7	3	1	220	60	0.93	5.96	6.15	6.36	51.79	31.75
8	3	2	180	70	0.86	7.49	7.81	10.88	52.86	32.2
9	3	3	200	50	0.39	5.84	6.85	0.99	58.86	40.48

Table 4: Response for signal-to-noise ratios "larger is better" for IB.

Level	Sorghum stalk	Bagasse	Pressing pressure	UFR concentration
1	0.7967	0.8933	0.82	0.6033
2	0.7567	0.8033	0.9467	0.8633
3	0.94	0.7967	0.7267	1.0267
Delta	0.1833	0.0967	0.22	0.4233
Rank	3	4	2	1

Table 5: ANOVA results for internal bonding strength (IB).

Control parameters	DOF	SS	V	F-test	P%
Sorghum stalk (SS)	1	0.01402	0.01402	0.6	4.17
Bagasse (B)	1	0.01307	0.01307	0.56	3.9
Pressure (P)	1	0.03082	0.03082	1.32	9.18
UFR concentration (UFR)	1	0.26882	0.26882	11.54	80
Error (E)	4	0.00931	0.00329	----	2.75
Total	8	0.33605			100

SS: sum of squares, DOE: degree of freedom, V: variance, P%: the percentage of contribution.

ratio was allocated to influence factors based on delta values in descending order; the highest delta value ranked the 1st, and the lowest delta value ranked the 4th. Generally, ranks show the relative importance of each factor to the response. Based on this scenario, the UFR is ranked in the first position, while the weight fraction of SB is found at the 4th level.

Table 5 gives ANOVA with the percentage of contribution of individual control parameters on IB. The UFR concentration and pressing load are the most significant control factors, while the reinforcement phases are the less significant factors in determining the internal bonding of particles. At a high level of UFR concentration, the probability of delamination would be lower than that at lower levels.

UFR is the most significant control variable with a percentage contribution of 80.00%. In contrast, the weight fraction of SB is the less significant factor of 3.90% in affecting the IB of particleboard. At a higher pressure level (22 MPa) and higher UFR concentration level, the value of IB will be comparatively higher than the other variables with their levels. The particleboards' IB will be increased as the pressing pressure increases from 18 MPa to 22 MPa since the pressing pressure was increased. Therefore, there is a probability of avoiding a gap-free surface area that weakens the bonding between particleboard particles. The above mean effect signal-to-noise ratio graphs shown in Figure 6 were plotted and show the optimum combination factors for the better performance of particleboard, particularly for IB. It is concluded that, for the higher IB strength, the optimal parametric combination is SS2SB1P3UFR3.

3.3. Modulus of Rupture (MOR).

Based on JIS A 5908 : 2003 standard, 8.0 N/mm^2 and 2000 N/mm^2 are the minimum requirements for MOR and MOE of particleboard panels for general use, respectively. The particleboard panel type #4 had the required MOR, and all panels satisfied the minimum requirement to MOE for general purposes [27].

The S/N ratio influences factors on response parameters based on delta values in descending order. It shows the relative importance of each factor to the response. For example, Table 6 illustrates that UFR concentration is ranked in the first position while the weight fraction of bagasse is found at the 4th level. Consequently, UFR concentration is relative to the most critical control factor to the MOR. The greater average S/N ratio corresponds to the maximum bending strength and the larger observed value represents the better board performance in terms of the modulus of rapture. The weighting method is used in this study to integrate the loss functions into the overall loss function. The overall loss function value is converted into a

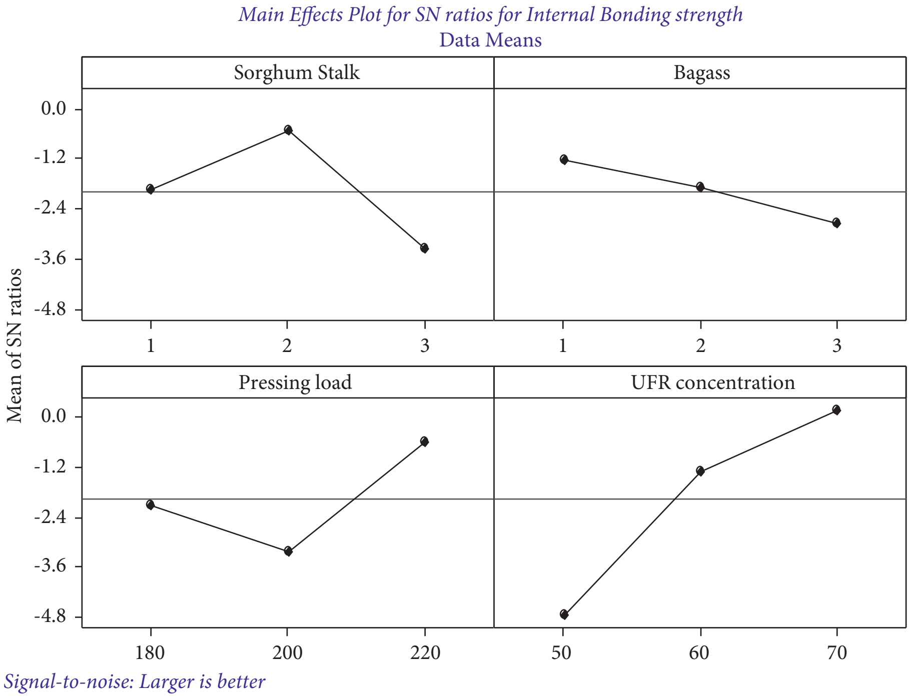


Figure 6: Main effect plot for the SN ratio for internal bonding strength.

Table 6: Response for signal-to-noise ratios “larger is better” for MOR.

Level	Sorghum stalk	Bagasse	Pressing pressure	UFR concentration
1	15.97	15.48	15.67	14.23
2	16.07	16.12	17.09	16.07
3	15.61	16.05	14.89	17.35
Delta	0.46	0.65	2.2	3.12
Rank	4	3	2	1

Table 7: ANOVA results for flexural strength (MOR).

Control parameters	DOF	SS	V	F-test	P%
Sorghum stalk (SS)	1	2.38	2.191	0.07	3.25
Bagasse (B)	1	3.079	3.981	0.24	4.21
Pressure (P)	1	22.446	22.023	0.29	30.71
UFR concentration (UFR)	1	42.167	42.752	17.01	57.69
Error (E)	4	1.021	0.958	----	4.14
Total	8	73.093			

SS: sum of squares, DOE: degree of freedom, V: variance, P%: the percentage of contribution.

signal-to-noise (S/N) ratio. In the analysis of the S/N ratio, the quality characteristic is usually divided into three categories: lower the better, higher the better, and nominal the better. Based on the S/N analysis, the S/N ratio for each level of process parameter is computed. A large S/N ratio corresponds to a better quality characteristic regardless of the category of the quality characteristic. As a result, the level of process parameters with the highest S/N ratio is the optimal level.

Table 7 shows ANOVA with the percentage of contribution of individual factors on flexural strength. The UFR concentration is the most significant control factor with the contribution percentage (57.69%). At the same time, the weight fraction of SS is the less significant factor (3.25) in affecting the flexural strength of particleboard. The mean effect plot for the S/N ratio response graph for the modulus of the rapture is shown in Figure 7.

The greater average S/N ratio corresponds to the maximum MOR. The larger observed value represents the better performance of particleboard in terms of bending strength. Therefore, it is concluded that the optimal combinations of variables for bending strength are 1 : 1 (SS : B), 200 bar pressing load, and 70 kg/m^3 UFR (SS1B1P2UFR3). Particleboards made with higher UFR concentrations have a high MOR and MOE. At higher UFR concentration (70 kg/m^3) and higher pressing pressure level, bending strength will be comparatively higher than the others. Due to the high amount of resin available per unit area, a lower surface area per unit weight will produce high bending strength.

3.4. Modulus of Elasticity (MOE).

The mathematical difference between the higher signal values to the lower signal value of levels was the delta value. This value determines variables' relative importance as delta values descend from the 4th level to the 1st level. Table 8 proves that UFR concentration is ranked in the 1st position while the weight fraction of sorghum was found at the 4th level. Henceforth, UFR concentration is the most critical control factor for the modulus of rupture (MOE).

Table 9 gives ANOVA with the percentage of contribution of individual control parameters on the MOE. The percentage of contribution of the control parameters is represented in a graph shown in Figure 8.

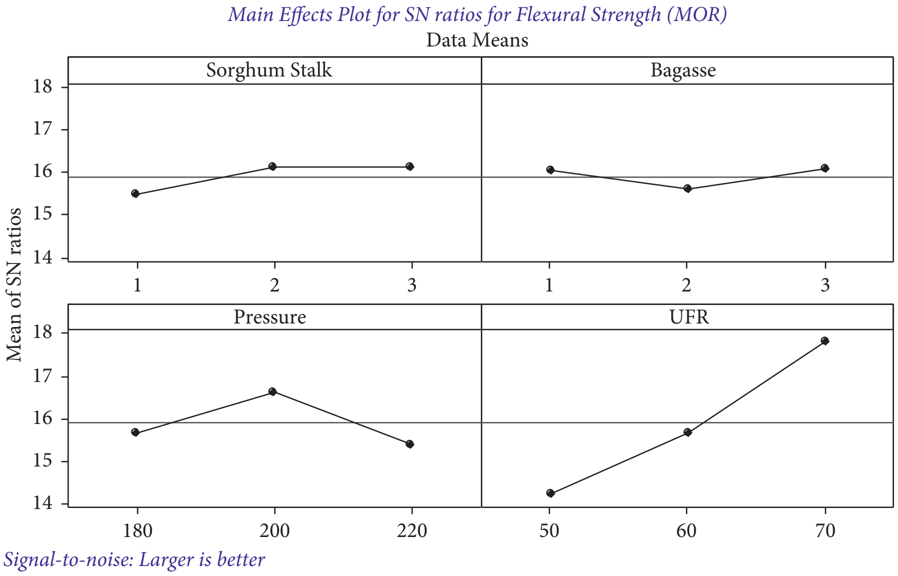


Figure 7: Main effect plot for the SN ratio for modulus of rupture (MOR).

Table 8: Response for signal-to-noise ratios "larger is better" for MOE.

Level	Sorghum stalk	Bagasse	Pressing pressure	UFR concentration
1	17.3	15.98	15.84	14.29
2	17.25	17.99	19.61	18.47
3	16.78	17.35	15.87	18.56
Delta	0.51	2.01	3.77	4.27
Rank	4	3	2	1

Table 9: Analysis of variance for MOE, using adjusted SS for tests.

Control parameters	DOF	SS	V	P%
Sorghum stalk (SS)	2	2.1515	1.0757	4
Bagasse (B)	2	4.7522	2.3761	8.84
Pressure (P)	2	24.2128	12.1064	45.03
UFR concentration (UFR)	2	22.6556	11.3278	42.13
Error (E)	0	—	—	
Total	8	53.7721		100

SS: sum of squares, DOE: degree of freedom, V: variance, P%: the percentage of contribution.

The analysis of variance for modulus of elasticity, using adjusted SS for tests, shows a figurative indication of to what extent a particular control factor affects the specified response [28–35]. Hence, the pressing pressure is the most significant control variable, with a percentage contributing 45.03%. In contrast, the weight fraction of SS is the less significant factor affecting the MOE. The best combination of factors as it can be examined from the S/N ratio of analysis of Taguchi is level one (1), level two (2), level one (200), and level two (60) for sorghum stalk to bagasse ratio, pressing load, and UFR concentration, respectively. On the other hand, the most significant parameter to increase board stiffness is the pressing pressure and then UFR concentration, the weight percentage of bagasse, and sorghum, respectively. Hence, the optimal combinations of variables for MOE are SS1SB2P2UFR3.

3.5. Board Density (BD).

3.5. Board Density (BD). Density is one of the physical parameters of composite that has a critical influence on the performance of particleboard. The actual density of particleboard is often less than the theoretical density due to the presence of voids in the board. It indicates that the highest volume fraction of voids in the particleboard usually leads to a greater susceptibility to water penetration, dimensional instability, and lower fatigue resistance [24]. The actual and theoretical densities of the particleboard with its corresponding volume fraction of voids are shown in Table 10.

3.6. Board Moisture Content (MC %). The maximum permissible moisture contents (JIS A 5908 : 2003) for the general purpose panel (Type 8) are 5% to 13%. The moisture contents of particleboards from Table 3 ranged from 4.39% to 10.88%, which is acceptable by referring to JIS A 5908 : 2003, and all test panels had the required level for the intended purpose.

The delta value of particleboard's MC is used to determine the relative importance of variables (reinforcement phases, pressure, and UFR concentration) as delta values were descending from 4th rank to 1st rank. Accordingly, Table 11 shows that UFR concentration is ranked in the 1st position while the SS was found at the 4th level. Therefore, UFR concentration is relative to the most critical control factor for the MC of row boards. A statistical analysis of variance was performed to identify the statistically significant process parameters.

Based on the formulas, we made calculations in Table 12 for finding the percentage of contribution of individual control parameters on the MC. The most significant parameter for reducing moisture content is UFR concentration and then pressure, sorghum stalk, and the weight percentage of bagasse of 37.64%, 34.76%, 16.77%, and 10.83%. Hence, UFR concentration and pressing load are the most significant control variables. In contrast, the weight variation of

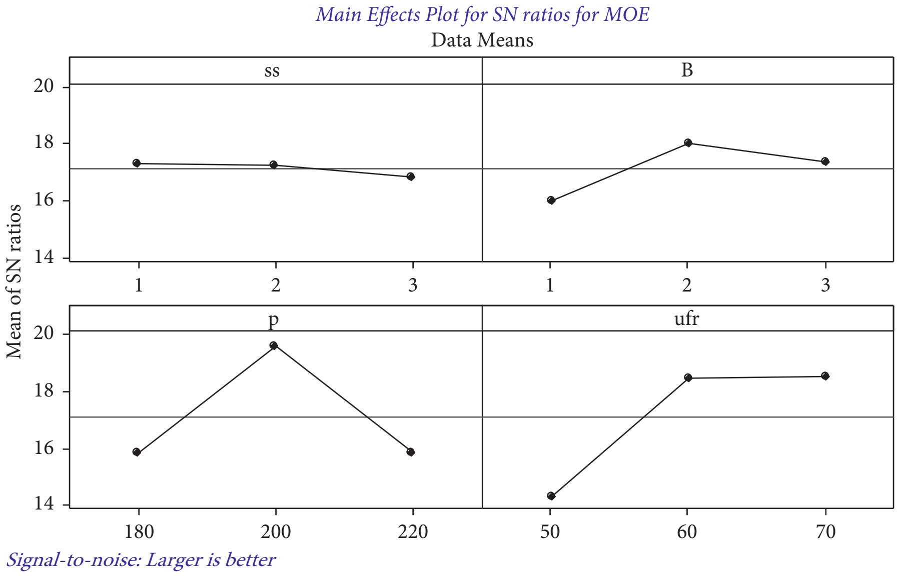


Figure 8: Main effect plot for the SN ratio for modulus of elasticity (MOE).

Table 10: Actual and theoretical densities of the particleboard.

# Experiment	1	2	3	4	5	6	7	8	9
Ave. Thickness (mm)	8.08	8.35	8.21	7.78	8.02	8.50	7.25	7.87	7.65
Ave. Mass (g)	12.20	13.23	11.54	11.25	12.23	12.89	9.98	11.52	12.09
Theoretical density (ρ) (g/cm^3)	0.604	0.634	0.562	0.593	0.610	0.607	0.551	0.586	0.632
Actual density (ρ) (g/cm^3)	0.442	0.422	0.410	0.419	0.457	0.487	0.457	0.425	0.417
Volume fraction of voids (%)	0.37	0.51	0.37	0.34	0.33	0.25	0.21	0.38	0.52

Table 11: Response for means of Moisture Content (MC %).

Level	Sorghum stalk	Bagasse	Pressing pressure	UFR concentration
1	−17.95	−18.04	−17.84	−10.68
2	−15.04	−17.09	−12.12	−15.75
3	−12.24	−10.1	−15.27	−18.79
Delta	5.71	7.94	5.72	8.11
Rank	4	2	3	1

sorghum stalk and sugarcane bagasse is the less significant factor in determining particleboards' moisture uptake properties.

The level average responses from the S/N ratio data help analyze the trend of quality characteristics concerning the variation of the factors under study. From the above values, graphs were plotted inferring the combination of variables, resulting in lower moisture content because of lower S/N ratio values. The response graph is shown in Figure 9. It is concluded that the optimal parametric combination for a lower percentage of moisture content is SS3SB1P3UFR3.

At higher urea-formaldehyde level UFR3 and higher pressing load level P3, moisture content (MC) would be comparatively lower than the other levels having lower resin concentration and press load. At the same time, the higher weight fraction of sorghum stalk from the reinforcement phases will improve moisture up-taking properties of particleboards because of the hydrophobic nature of sorghum bark.

3.7. Water Absorption.

Composites were immersed in the distilled water with a temperature range of 20–25°C for about 24 hours, and the weight gain and the variation of thickness were recorded within 24-hour intervals. It is noted that composites with lower pressing loads have absorbed the most moisture when soaked in the distilled water at a temperature range of 21–25°C for the same period of conditioning time. A statistical analysis of variance was performed to identify the statistically significant process parameters. The control parameter's contribution percentage is represented in Table 13.

As per the ANOVA result, using SS for tests, the most significant parameter for reducing water absorption is the weight percentage of sorghum stalk (48.05%), and the lower significant variable was pressing load (6.78%). While dealing with "smaller is better", it is required to consider the main effects of the S/N ratio with the lowest point from the given levels to determine the best combination and the significant factor. Water absorption decreases with an increase in the weight percentage of SS and a decrease in the average value of bagasse. Therefore, the increment in SS resulted in a decrement in water absorption. The amount of weight percentage of SS directly affects the water segregation into discrete fibers because of the hydrophobic nature of sorghum bark. Therefore, the amount of weight increment on the particleboard would be lower at a higher level of sorghum. Hence, it is advisable to have a higher percentage of SS to lower the boards' water absorption. The graphs provided by Taguchi's

Table 12: ANOVA results for board moisture content (MC %).

Control parameters	DOF	SS	V	P%
Sorghum stalk (SS)	2	11.8392	5.9196	16.77
Bagasse (B)	2	7.6373	3.8186	10.83
Pressure (P)	2	24.5325	12.2662	34.76
UFR concentration (UFR)	2	26.5673	13.2836	37.64
Error (E)	0	—	—	
Total	8	70.5762		100

SS: sum of squares, DOE: degree of freedom, V: variance, P%: the percentage of contribution.

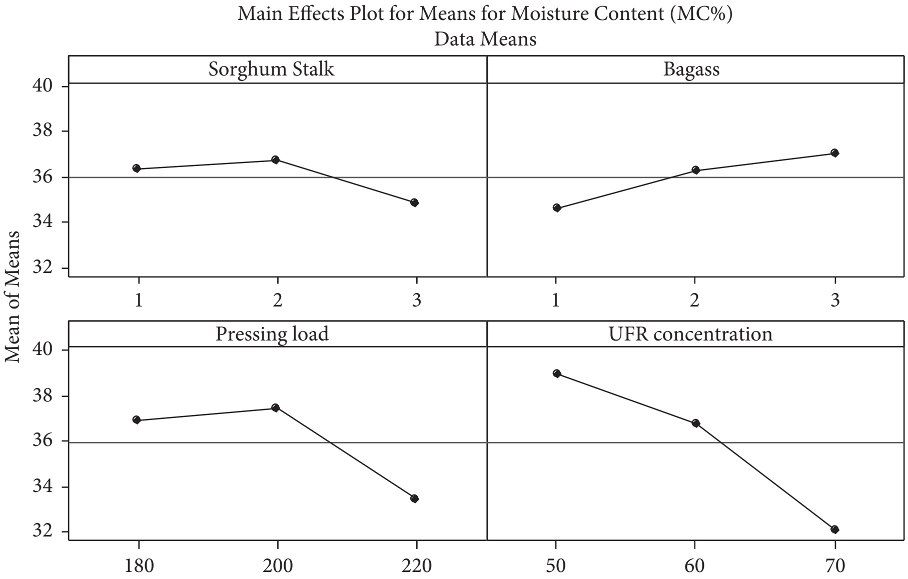


Figure 9: Main effect plot for means of moisture content (MC %).

Table 13: Analysis of variance for water absorption, using adjusted SS for tests.

Control parameters	DOF	SS	V	F-test	P%
Sorghum stalk (SS)	1	36.8	36.8	0.66	48.05
Bagasse (B)	1	11.1	11.1	0.2	14.62
Pressure (P)	1	5.15	5.15	0.09	6.78
UFR concentration (UFR)	1	21.62	21.62	0.39	28.48
Error (E)	4	4.21	2.1	—	5.54
Total	8	75.92			100

design analysis show the main effects of the plot for the S/N ratio and the main effects for water absorption versus the four parameters as indicated in Figure 10.

The lower observed S/N ratio value represents the better performance of particleboard in water absorption characteristics. Accordingly, the best combination of the experiment design showing the lower water absorption value was SS3SB2P2UFR2.

3.8. Thickness Swelling. The test is conducted by immersing specimens entirely in the enclosed filled tank in distilled water with a temperature range of 20–25°C. The variation of thickness was recorded within 24-hour intervals. Then, the thickness variations of the composite materials were calculated using an equation and the average results.

During 24 hrs, water soaking resulted in TS ranging from 32.2% to 40.48%, as shown in Table 3. The maximum permissible TS for 24 hrs (EN 312–4 (1996)) is 15% for panels used for construction and/or furniture manufacturing industries for human residence. The results presented in Table 3 show that any of the test boards had the required level of TS due to the minimum amount of paraffin wax in the manufacturing of tested board panels. Spring back of panels due to socking of water is the major drawback of wood composite, and it leads to less dimensional stability [11].

The S/N ratio response was allocated to influence factors based on delta values in descending order; the highest delta value was ranked 1st, and the lowest delta value was ranked last. Ranks show the relative importance of each factor to the response parameter. For example, Table 14 infers that UFR concentration is ranked prior while the sorghum stalk was found at the 4th level. It implies that UFR concentration is relative to the most important control factor for the swelling of particleboards.

Table 15 gives ANOVA and F-test values with a percentage of individual control parameters on TS. The percentage of contribution of the control parameters is represented in a graph shown in Figure 11. It is clear that the control parameters like UFR concentration and pressing load are the most significant control factors, and sugarcane bagasse sorghum stalk is the less significant factor in determining the

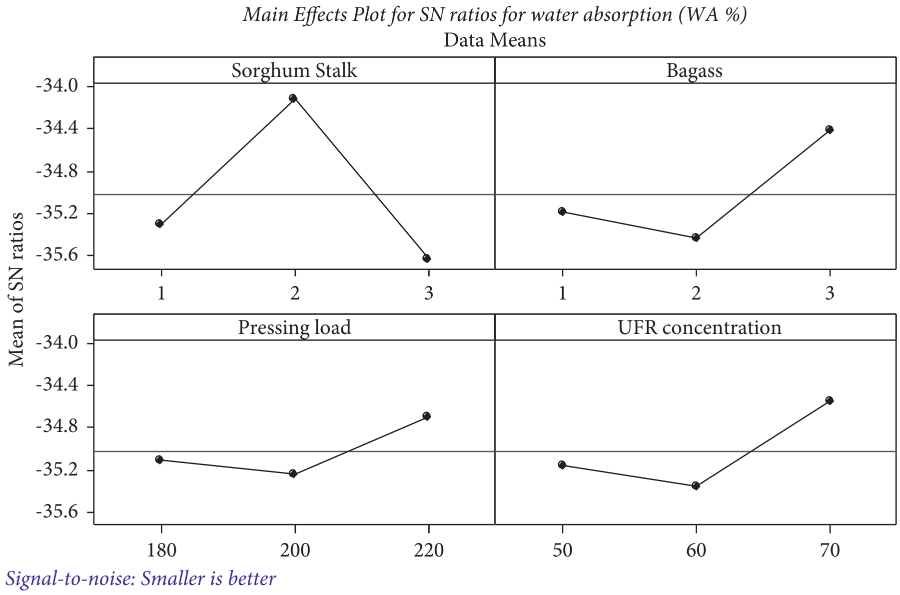


Figure 10: Main Effects Plot for S/N ratio for water absorption.

Table 14: Response for effects plot for mean "smaller is better" for thickness swelling.

Level	Sorghum stalk	Bagasse	Pressing pressure	UFR concentration
1	36.33	34.56	36.91	39
2	36.67	36.25	37.48	36.77
3	34.81	37	33.42	32.04
Delta	1.86	2.45	4.06	6.95
Rank	4	3	2	1

Table 15: Analysis of variance for thickness swelling, using adjusted SS for tests.

Control parameters	DOF	SS	V	F-test	P%
Sorghum stalk (SS)	1	3.466	3.466	0.83	2.89
Bagasse (B)	1	8.979	8.979	2.15	7.49
Pressure (P)	1	28.2	28.2	6.36	23.52
UFR concentration (UFR)	1	72.523	72.523	17.37	60.51
Error (E)	4	6.705	4.176	—	5.59
Total	8	119.874			100

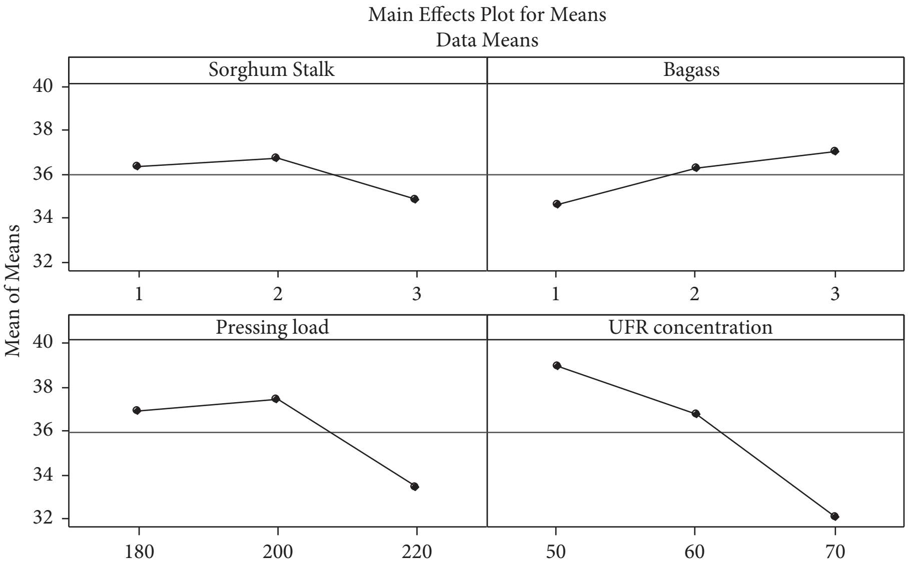


Figure 11: Main effects plot for means of thickness swelling.

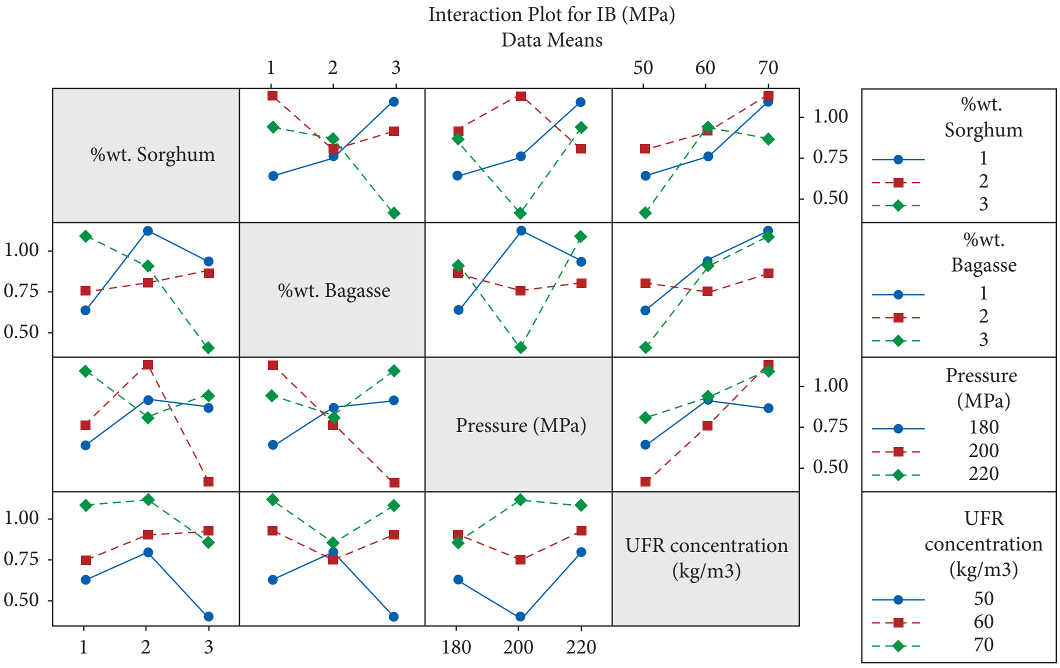


Figure 12: Interaction effects plot for IB (MPa).

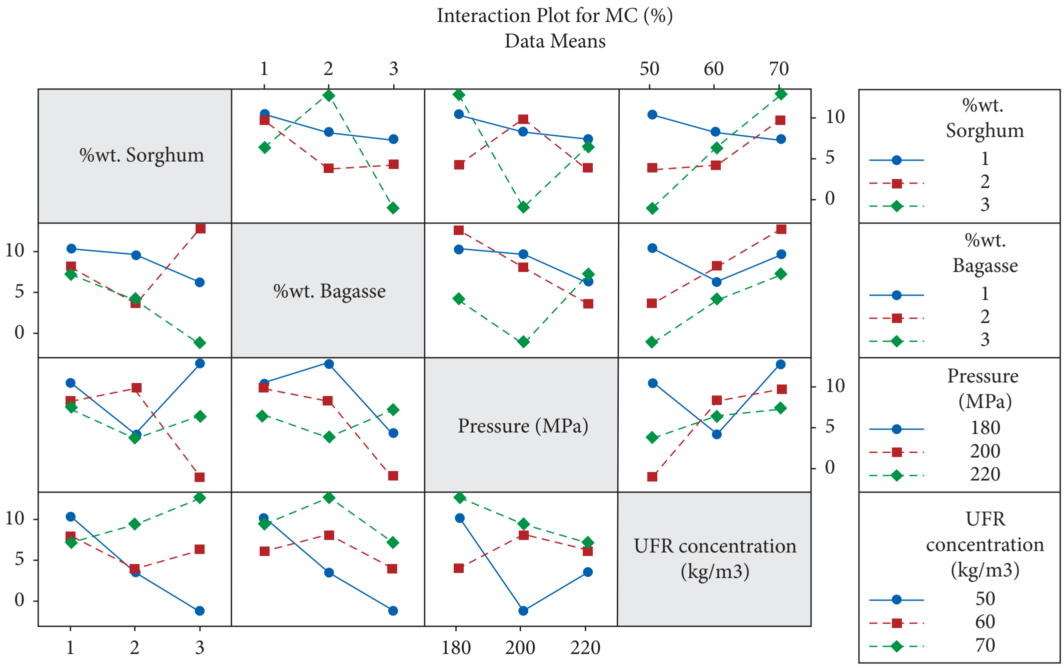


Figure 13: Interaction effects plot for MC%.

TS. At a high level of UFR concentration, the amount of thickness variation would be higher than at the lower values. The graphs' values were plotted, inferring the average effect of control factors on the thickness variation. The S/N response graphs infer that for lower thickness swelling (TS), the optimum parametric combination will be SS3SB1P3R3.

The amount of UFR directly affects the dislocation of discrete fibers and particles. Therefore, the dimensional variation on the particleboard will be more incredible at lower UFR concentrations. Hence, it is preferable to have a high resin concentration to have lower thickness swelling. The amount of UFR directly affects the dislocation of discrete fibers and particles.

This process of determining the best combination of input process parameters to produce the desired output parameters necessitates the execution of several experiments, which takes a significant amount of time and money. Several efforts have been made to comprehend the effect of

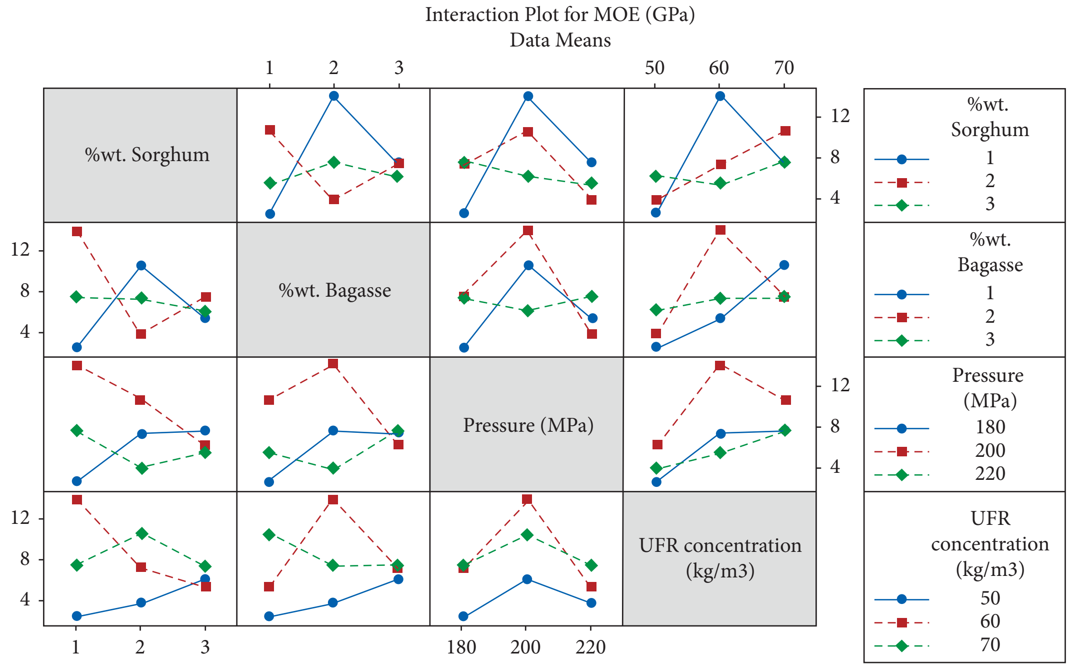


Figure 14: Interaction effects plot for MOE (GPa).

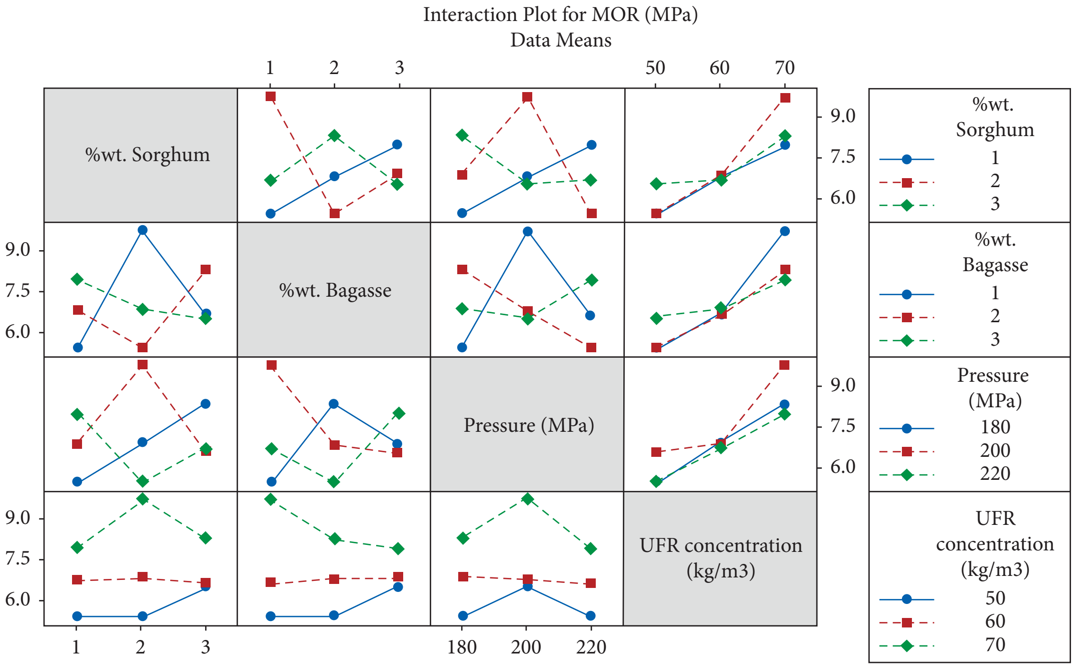


Figure 15: Interaction effects plot for MOR (GPa).

process parameters shown in Figures 12–17, and it can be deduced that higher output process parameters could be obtained when the input process parameters are optimized to achieve the larger to better. To consider multiple quality characteristics when selecting process parameters, the Taguchi method must be modified to evaluate multiple loss functions corresponding to different quality characteristics. Taguchi's parameter design can optimize performance by adjusting design parameters and reducing system performance fluctuation due to sources of variation.

Therefore, the dimensional variation on the particleboard will be more incredible at lower UFR concentrations. Hence, it is preferable to have a high resin concentration to have lower thickness swelling. The addition of sorghum stalk effectively decreases the water absorption and thickness swelling properties of particleboards. It is because of the hydrophobic nature of sorghum stalk bark. Finally, the SS and SB hybrid with a [3 : 1] ratio is an attractive fit for particleboard production. The major contribution of sorghum stalk (SS), followed by UFR concentration (UFR),

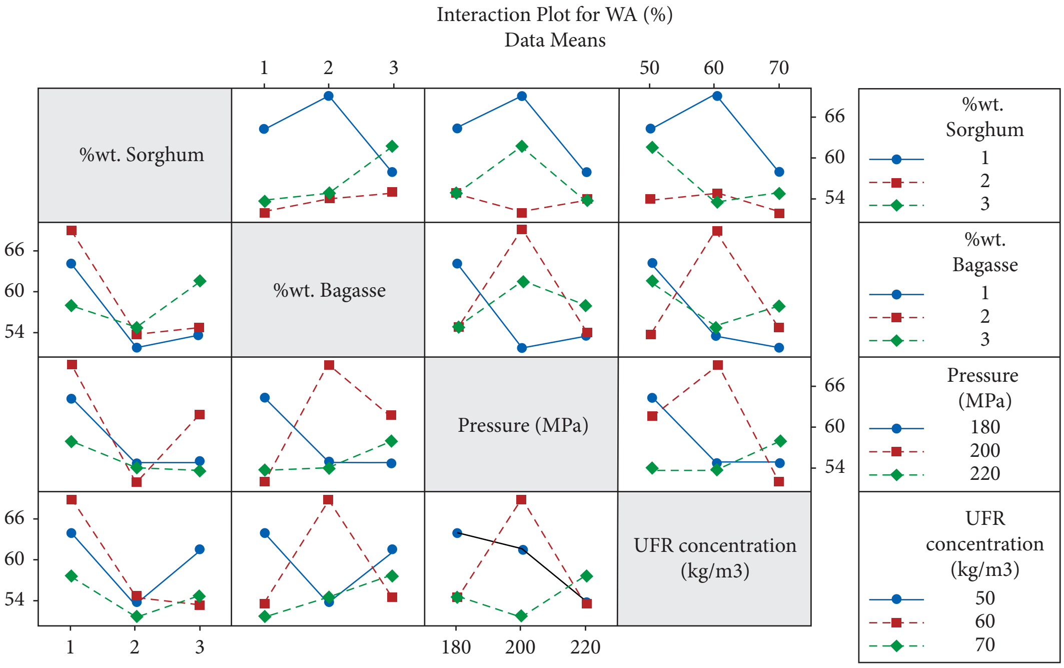


Figure 16: Interaction effects plot for WA %.

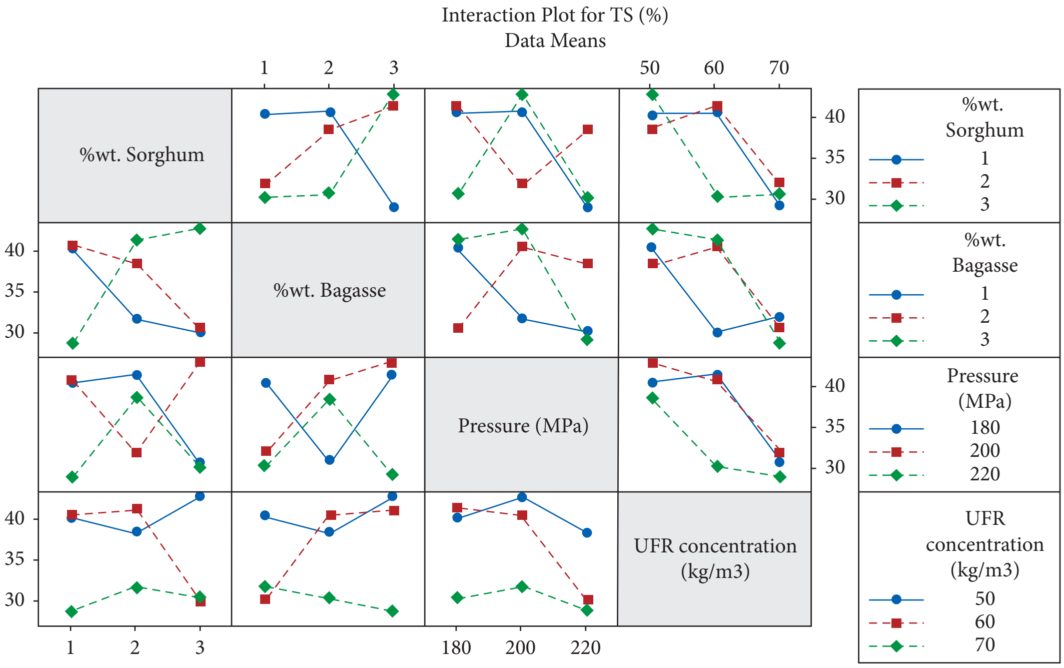


Figure 17: Interaction effects plot for TS (MPa).

bagasse (B), and pressure (P), is 48.05 percent, 28.48 percent, 14.62 percent, and 6.78 percent, respectively.

4. Conclusions

This study found the combination of the optimal variables for particleboards made from sorghum stalk and sugarcane bagasse by varying control variables through the Taguchi design approach L9 orthogonal array. The following conclusions are formulated from the exponential results and statistical analysis of variance. First, for all response parameters except water absorption, urea-formaldehyde concentration is a highly influential variable, and it is observed that an increase in urea-formaldehyde resin from 50 kg/m^3 to 70 kg/m^3 increases internal bonding. As learned from statistical analysis of variance (ANOVA), resin concentration shows a high influence while the weight percentage of sorghum stalk shows the slightest influence on most response parameters. The ANOVA results provide the most optimized combination of variables for composite particleboards and conclude that SS3SB1P3UFR3 is the optimum parametric combination for better performance. The increase in weight percentage of sorghum stalk dramatically reduces the water absorption and thickness swelling properties of particleboards. It is due to the hydrophobic nature of sorghum stalk bark. Finally, the SS and SB hybrid with a ratio of [3 : 1] is a good candidate for particleboard production.

Data Availability

All data are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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