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Article

Physical and Mechanical Properties of Binderless Corn Stover Bioboards

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Abstract

The elimination of toxic and synthetic binders from the manufacture of fibreboards and particleboards is important, considering environmental and health implications. The utilization of agricultural waste for the manufacture of boards is also beneficial to waste management and enhances sustainability in the manufacturing of boards. In this study, corn stover was utilized in the manufacture of binderless bioboards. The influence of production factors, or manufacturing parameters, on the physical and mechanical properties of the bioboards was investigated. The bioboards had a density between 669.9 kg/m^3 and 986.4 kg/m^3, and the water absorption was between 165% and 237%. The bioboards had modulus of elasticity ranging between 13.3 and 85.6 MPa, whilst the modulus of rupture varied between 0.149 and 0.835 MPa. Also, the internal bond strength of the corn stover boards varied between 0.43 and 1.17 MPa. Particle size emerged as the dominant parameter governing density, hygroscopic behaviour, and mechanical performance, indicating that fibre packing and interlocking outweighed thermal softening effects with the investigated processing parameters. Further treatment of the corn stover is required to improve the application of the boards for load-bearing and structural applications.

Keywords: binderless boards; manufacturing parameters; bioboards; corn stover; mechanical properties

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1. Introduction

Fibreboards are engineered wood composites produced from lignocellulosic fibres, often using synthetic binders or resins, consolidated under heat and pressure. Depending on their properties, they are classified as low-, medium-, or high-density fibreboards. Fibreboards can be used in various applications, including furniture, semi-structural applications, insulation, and soundproofing [1]. Particleboard, composed of larger particles such as wood chips, shavings, or sawdust bonded together using a resin or wax [2], is manufactured by hot pressing wood chips into panel form, and has a high demand in the global market [3]. Particleboard is produced by forming reduced timber particles into a panel, using a synthetic resin, traditionally urea-formaldehyde or phenolic-formaldehyde. Other resins, such as methylene diphenyl diisocyanate, have been utilized [4]. There is progress in research into the utilization of non-formaldehyde-based binders because these resins affect indoor air quality, having a negative impact on human health and the environment [5].

According to Jones and Brischke [6], the main structural constituents of the wood cell wall are cellulose, hemicellulose, and lignin. The cell wall also contains other polymeric compounds in lesser amounts, including starch, pectin, and proteins. Some researchers have used agricultural waste materials to produce particleboards [7]. Bioboards are produced from lignocellulosic biomass fibre using bio-based and natural binders rather than synthetic binders [8]. Research has been conducted using various non-wood plants and fibres as well as agricultural residues. The intention is that these could replace conventional woods in the manufacture of bioboards [9].

Due to waste management issues, several agricultural residues pose environmental problems, except for those consumed as animal feed. Several studies also report an abundance of these biomass resources globally and regionally [10,11]. The effective utilization of agricultural residues could solve the waste management problems whilst enhancing sustainability in the manufacturing of engineered boards. There is increased consideration for the development of binderless boards that rely on the natural binding components within biomass. However, the concerns are about the boards' quality, which affects their applicability.

Khoo et al. [12] proposed the utilization of natural mycelium obtained during the cultivation of mushrooms as a natural adhesive for high-performance bioboard. The optimal temperature was found to be 160 °C for 20 min at 10 MPa. Internal bond strength of the boards produced was up to 2.51 MPa. Song et al. [13] assessed the importance of temperature on the mechanical properties and dimensional stability of bioboards produced from soybean straw. It was observed that the dimensional stability of the bioboard improved as the temperature increased from 140 to 230 °C. Song et al. [8] developed a hybrid bioboard using fibre from soybean straw with polylactic acid as the binder and studied the effects of pressure on the properties of the bioboard. The study found that with the added binder, the bending and tensile strengths of the bioboard decreased.

Xiao et al. [14] investigated the influence of hot pressing temperature on the mechanical properties and dimensional stability of bioboards produced from reed straw treated with an alkali solution. It was observed that 180 °C provided the optimal performance, with the board cross-section showing high compaction. Fan et al. [15] developed a binderless bioboard from eggplant straw fibres using pressures between 2 and 8 MPa. The bending rupture stress increased with increasing pressure from 27.69 to 45.29 MPa, but water absorption decreased from 91.45 to 88.29%.

Orisaleye et al. [16] studied the effect of processing parameters on the bioboard properties using milled corncobs. The study found that the particle size was an especially important parameter in determining the density, modulus of elasticity, modulus of rupture and internal bond strength of the bioboard. Apart from density, the other properties were below recommended values. Orisaleye et al. [17] also investigated the production of binderless boards using untreated sawdust. The study found that pressure and pressing temperature were the most significant factors in determining density, modulus of elasticity and internal bond strength. Ogundare et al. [18] utilized response surface methodology to characterize bioboards produced from sawdust and found that pressure and temperature significantly determined the density and modulus of elasticity of the bioboards. Cai

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et al. [19] evaluated the influence of pressure on properties of a biodegradable board developed for fibre insulation using camphor branches. The study showed that increasing the applied pressure enhanced the mechanical properties, hygroscopic behaviour, and fire resistance of the board.

From the studies, the major factors influencing the properties of the bioboards are the pressure, pressing temperature, pressing time, and particle shape and size. Rather than a single dominant factor, these factors interact together to determine the self-bonding mechanism of the bioboards [16–18]. The primary driver for bonding is the thermal softening and plasticisation of lignin. Lignin becomes mobile at elevated temperatures and coats the fibre or particles under applied pressure. It has been demonstrated in some previous studies [20–22] that between 90 and 150 °C, lignocellulosic biomass undergoes a glass transition. This refers to the change of state of the constituent polymers (lignin, hemicellulose, and cellulose) from a hard glassy state into a soft rubbery state. Beyond the glass transition temperature, lignin condensation and hemicellulose thermal degradation occur simultaneously, and the resulting reaction products form a three-dimensional crosslinked network between fibres. Elevated temperature also activates protein as a natural binder and influences the rearrangement of the cellulose crystalline structure, thereby affecting the mechanical performance, water resistance, and thermal stability of the final material. The physical entanglement of the interconnected fibres occurs because of friction, and this improves the self-bonding of particles during board formation [22].

Macroscopically, binding mechanisms can be classified into bonding occurring through solid bridges between particles and bonding without a solid bridge. Solid bridges are developed under pressure when molecules diffuse from one particle to another at the points of contact. Above the glass transition temperature and under high pressure, the natural binders are pressed out of the material and cause inter-particle bonding, and this creates a solid bridge when the melted constituents solidify. When solid bridges are not formed, particles bind together through hydrogen bridges, van der Waals' forces, and electrostatic and magnetic forces if the particles are in proximity. Some other bonding mechanisms that strengthen internal bonding of boards are interfacial forces and mechanical interlocking [22,23]. Smaller particle size leads to more comprehensive interfacial or higher glue lines, which result in improved mechanical properties of binderless boards [24]. The bonding mechanism during the consolidation of biomass particles to form binderless boards varies and depends on the raw materials and the specific manufacturing process [22,25].

It has been noted that the increase in temperature during the production of bioboards improves the lignin softening, and consequently the properties of the bioboard to a certain extent before it becomes counterproductive [13]. Moreover, higher temperatures could lead to charring of the fibres or particles. The effect of the range of temperatures resulting in charring has not been extensively studied, but Song et al. [13] noted that heating to 230 °C causes thermal degradation of soybean straw and does not significantly promote improvement to most mechanical properties despite achieving a smooth cross-section at 200 °C. In line with this, Xiao et al. [14] found that increasing temperature up to 180 °C improved the properties of the boards coupled with alkali pretreatment, which improved softening of the fibre and the creation of rough surfaces. The alkali treatment increased the friction between fibres and produced rich polar oxygen-containing functional groups on the surface, and this improved the self-bonding of the board.

The low internal bonding strength of formaldehyde-free bioboard produced from mushroom mycelium and substrate waste has been attributed to the partial rupture of microtubes within the cell [12]. A similar observation was made by Fan et al. [15], identifying several tubular pores and gaps on the eggplant straw boards, which could accommodate a large amount of air and water. As the applied pressure increases, the pores and gaps between the fibres decrease and the water resistance of the boards is improved. Other studies [16–18] have also identified micropores and voids within the boards, which have been attributed to insufficient pressure despite the particles being coated with lignin under elevated temperature. As described by Cai [19] for boards produced for camphor branches, applied pressure causes the cellulose molecules to be haphazardly stacked to form tiny voids, and hydrogen bonds are formed between free hydroxyl molecules on the fibre molecules. However, tiny voids block the formation of hydrogen bonds, but increasing applied pressure gradually reduces the tiny voids on the surface and section of the boards. Although Cai [19] noted that plasticization of lignin was not possible due to low temperature, it is apparent that a combination of pressure and temperature influences the self-bonding mechanism of the fibres during the production of the boards, and these also influence the performance of the boards. Orisaleye et al. [16] investigated the influence of particle size of corncobs and found that this significantly influences the properties of the boards, noting that the reduction in particle size results in a large surface area, which influences the quality of self-bonding. In line with this, Vitrone [1] and Marwadi et al. [24] note that particle sizes have a significant effect on board properties, with finer particles improving the water resistance and larger particles improving bonding strength. Marwadi [24] also notes that larger particle size leads to more comprehensive interfacial or higher glue lines, which increases the flexural strength of the boards. The presence of lignin bridges constitutes the core mechanism enabling self-bonding in binderless boards [26]. Hot pressing temperature significantly influences the bonding mechanism, with hydrogen bond rearrangement being prevalent at lower temperatures and lignin softening at higher temperatures [27]. Mechanical interlocking has also been identified as a binding mechanism that causes complex networks around discrete particles [26,28].

Corn stover is a byproduct of maize processing that is produced in several regions across the world in massive quantities [10,11,29]. It is the non-grain portion of the corn plant and consists of the leaves, stalks, and husks. Corn stover generates substantial residue that needs to be harnessed sustainably to develop bioproducts. In post-harvest processes of conventional agricultural systems, corn stover is frequently managed through open-field burning or left to decompose unchecked. The utilization of corn stover for bioboard production could enhance the drive towards sustainability and principles of the circular economy, which involves repurposing the corn stover to ensure that it is kept in use, and the natural systems are regenerated. Moreover, the use of corn stover and suitable agricultural wastes for bioboard production reduces the dependence on wood resources for application in the production of boards used for various applications.

There has been a huge focus on using corn stover for bioenergy applications with little consideration of other significant high-value applications. Corn stover contains cellulose, hemicellulose, and lignin [30], which makes it a potentially useful material to produce bioboards through the exploitation of the lignin content for self-bonding. Aside from being environmentally friendly and sustainable, corn straw is known to possess high cellulose content and low density, which makes it suitable for applications requiring materials with good mechanical strength and light weight. Particleboards from corn straw can attain acceptable mechanical properties compared to conventional wood particle boards [31–34]. Self-bonding eliminates the use of eco-toxic chemical inputs applied during the production of particleboards and fibreboards. However, it is important to identify the factors that significantly influence the quality of bioboards produced from corn stover, and to study the effects of their interactions.

Corn stover possesses distinct structural and compositional characteristics that are different from those of other lignocellulosic materials that have been used in the production of binderless boards. It has high hemicellulose content and, in contrast to other binderless

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board feedstock, heterogeneous fibre morphology consisting of the stalk, leaves and husks. This may lead to a distinct packing behaviour which has not been extensively studied in the literature to determine the effect of processing parameters on the self-bonding behaviour. Hence, a study on the utilization of corn stover in the production of binderless boards is necessary to determine its suitability and limitations for producing binderless boards. In this study, the effect of key processing parameters such as pressure, pressing temperature, pressing time and particle size on the physical properties (including density, water absorption and thickness swelling) and mechanical properties (modulus of elasticity, modulus of rupture, and internal bond strength) of bioboards produced from corn stover is systematically investigated. The novelty of this study lies in the systematic evaluation of the combined effects of key processing parameters for bioboard production from corn stover.

2. Materials and Methods

2.1. Acquisition and Processing of Corn Stover

Corn stover was acquired after maize was harvested from a farm in Ipokia Local Government Area, Ogun State, Nigeria, West Africa. The collected corn stover was air-dried to reduce moisture content to about 14% and condition it for size reduction. After drying, the corn stover was milled using a combined chopping and milling machine based on the design of Orisaleye et al. [35]. The combined chopping and milling machine has a two-stage size reduction process for stalks but a single stage for non-stalk biomass. The combined chopping and milling machine consists of chopping knives that are attached to the rotating shaft. The corn stover is fed through the side feeding port, where the chopping knives reduce it to smaller chips. After reduction by the chopping knives, the chopped stalk falls directly into the hammer mill chamber, where it is further reduced with hammers, carried on hammer rods, which beat against the material, which is prevented from exiting the machine by a screen mesh. As the hammers beat against the chopped stalks, they are reduced to particulate fibres until they can leave the machine through the sieve as they attain sizes smaller than the screen mesh sizes. The corn stover was milled to two different particle sizes using screen mesh sizes of 3 and 6 mm.

2.2. Laboratory Hot Press

The laboratory hot press used was designed and fabricated with a 50-tonne hydraulic jack to exert pressure on the material in the mould. The laboratory press produces a rectangular bioboard measuring 200 mm × 100 mm with varying thickness depending on the conditions applied during pressing. The laboratory hot press shown in Figure 1 has cartridge heaters in the top and bottom pressing moulds to increase the temperature of the compacted materials within the mould.

2.3. Bioboard Production

The bioboards from corn stover in this study were manufactured using the dry process. During operation, the bottom pressing block was aligned with the lower end of the mould. The temperature controller was then used to set the cartridge heaters to the desired temperature of 100 or 150 °C. Thereafter, 175 g of the milled corn stover was placed in the mould. The upper pressing block was secured in position on top of the mould, and the hydraulic jack was operated until a specified pressure of 9 or 15 MPa was reached. The setup was allowed to stand for a specified pressing time, after which the top pressing block was removed. To retrieve the formed bioboard, the hydraulic jack was operated until the formed bioboard could be picked from the top of the mould. Figure 2 shows the production process of the bioboards using the hot press.

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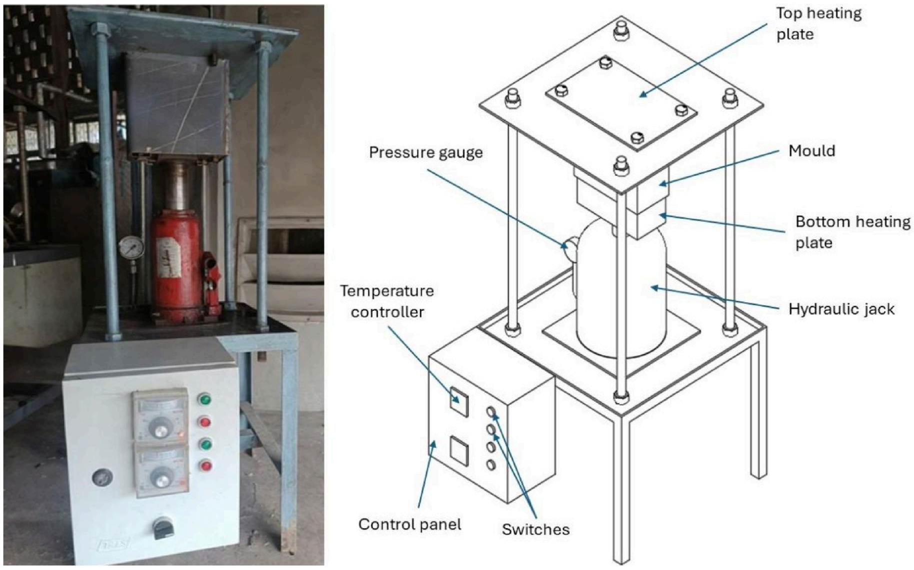

Figure 1. Laboratory hot press designed to produce bioboards.

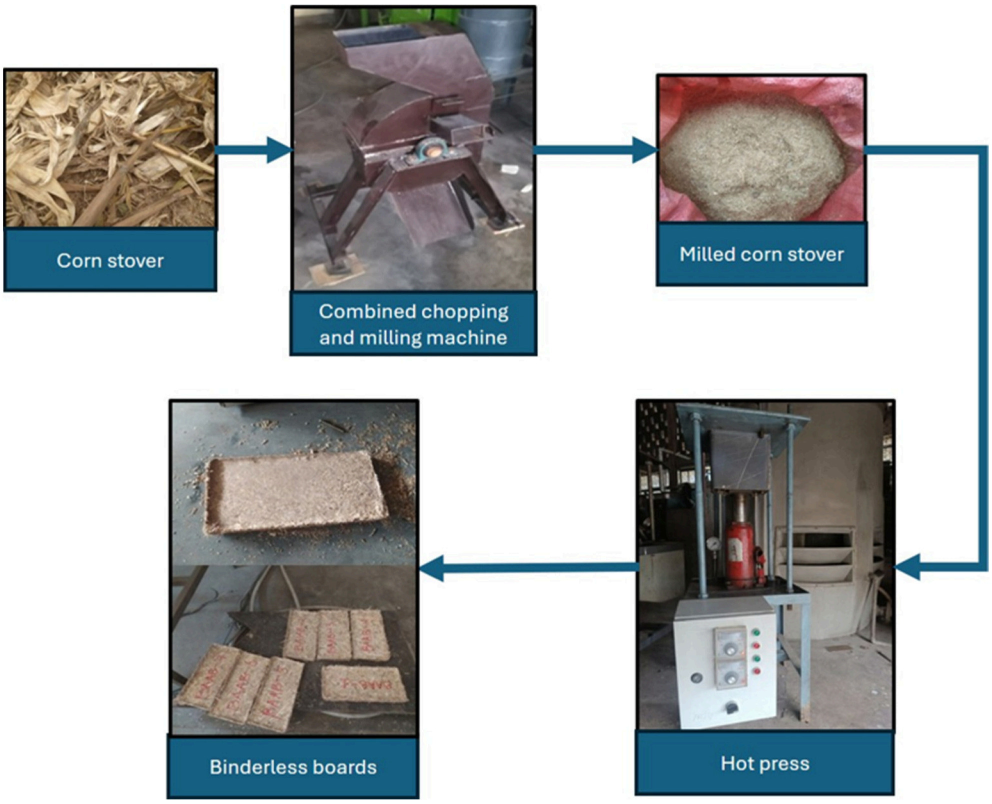

Figure 2. The production process for the binderless boards from corn stover.

2.4. Experimental Design

Prior to investigating the properties of the boards with the experimental design, preliminary trial samples were produced to identify the feasible operating conditions for the manufacture of stable and firm boards. The experiment was then designed based on the identified operating conditions to allow a systematic investigation of the effect of the manufacturing parameters on the properties of the bioboards. The systematic investigation allowed the investigation of the main effects and the interaction effects of the manufacturing factors on the bioboard properties, providing a more comprehensive analysis than the conventional one-factor-at-a-time method.

A fractional factorial design generated using Minitab statistical software (Minitab 21.2) was utilized for the study. The levels of the variables used were 9 and 15 MPa for pressure (P), 100 and 150 °C for temperature (T), 5 and 10 min for the pressing times (θ), and 3 and 6 mm for the milling screen mesh size (S). The experimental design is outlined in Table 1, and three replicates were used for each run, with the average of the replicates utilized for analysis. A total of 120 boards were produced during the study. The responses desired from the experimental design were the density, water absorption, thickness swelling, modulus of elasticity, modulus of rupture, and internal bond strength of the bioboards.

2.5. Determination of Physical Properties of Bioboards

2.5.1. Density

Density is a crucial factor in fibreboards and particleboards as it is used to classify boards into distinct types for various applications, and to determine other properties of bioboards. After forming the boards, the burrs at the edges of the boards were carefully removed using a file to ensure that a cuboidal shape was obtained. Board density is the ratio of the board's mass to its volume. The mass of the board was determined using an electronic mass balance. The volume was evaluated from the geometry of the bioboard, which was measured with a Vernier calliper. The Vernier calliper was used to take the measurements of the length, width, and thickness of the boards. To average out any errors, the dimensions were taken across different sections of the board, and the mean of the values was used as a representative value of the geometry. The density of the board was then determined using Equation (1).

$$\rho = \frac{m}{l \times w \times t} \quad (1)$$

From Equation (1), ρ is the density of the bioboard (kg/m^3), m is the mass of the bioboard (kg), l is the length of the bioboard (m), b is the width of the bioboard (m), and t is the thickness of the bioboard.

2.5.2. Water Absorption

Water absorption determines the applicability of the bioboard in a moist environment. The water absorption was determined by adopting the 24 h submersion method described in ASTM D1037-06a [36]. In this study, whole boards (200 mm × 100 mm × thickness mm) produced from the hot press were used in the determination of the water resistance after the edges had been smoothened and the boards dried in the oven. To determine water absorption, the mass of the test piece was measured using an electronic mass balance before it was immersed in a basin of water at room temperature for 24 h. The mass of the board was measured after the period of immersion. Water absorption was estimated as the ratio of the mass of absorbed water to the initial mass of the test samples, as expressed in Equation (2).

$$WA = \frac{m_f - m_i}{m_i} \times 100 \quad (2)$$

From Equation (2), WA is the water absorption (%), m_f is the mass of the bioboard after immersion in water (kg), and m_i is the mass of the bioboard before immersion in water (kg).

2.5.3. Thickness Swelling

Thickness swelling occurs due to absorption of moisture and is dependent on the absorption properties of the bioboard. Thickness swelling was determined from the water absorption test specimen by adopting the 24 h submersion method described in ASTM D1037-06a [36]. As with the water absorption test, whole boards (200 mm × 100 mm × thickness mm) produced from the hot press were used for the test after the edges had been smoothed and the boards dried in the oven. The thickness of the bioboard before and after immersion in water was determined using a Vernier calliper. The thickness swelling is estimated as the ratio of the change in thickness of the immersed bioboard to its initial thickness before immersion.

$$TS = \frac{t_f - t_i}{t_i} \times 100 \tag{3}$$

From Equation (3), TS is the thickness swelling (%), t_f is the thickness of the bioboard after immersion in water (mm), and t_i is the thickness of the bioboard before immersion in water (mm).

2.6. Determination of Mechanical Properties of Bioboards

2.6.1. Modulus of Elasticity

The modulus of elasticity is an evaluation of the degree of the board's stiffness, or ability for elastic deformation when subjected to stress. It is a measure of the relationship between stress and strain in the board when it is subjected to an external force. The modulus of elasticity of each bioboard was determined using ASTMD1037-06a standard test methods [36], with the 3-point static bending test conducted on a universal testing machine (Instron Machine, Series 3360, Instron, Norwood, MA, USA). The modulus of elasticity of the bioboard is the gradient of the linear plot of the load–deflection curve during the static bending test. The modulus of elasticity is obtained from Equation (4).

$$MOE = \frac{\Delta P}{\Delta y} \frac{L^3}{4wt^3} \tag{4}$$

From Equation (4), MOE is the modulus of elasticity (MPa), ΔP is the change in pressure within a portion of the proportional limit of the load–deflection curve (N), Δy is the corresponding change in deflection corresponding to ΔP within the proportional limit (mm), L is the span (mm), w is the width (mm), and t is the thickness (mm) of the specimen.

2.6.2. Modulus of Rupture

Modulus of rupture is critical to determining the application of the product for structural components. The modulus of rupture is the ultimate bending stress when subjected to a bending load and was determined using a 3-point bend test with an Instron Machine (Series 3360, Instron, MA, USA) according to ASTMD1037-06a [36]. The modulus of rupture is estimated from the load–deflection curve using Equation (5).

$$MOR = \frac{3LP_{max}}{2wt^2} \tag{5}$$

From Equation (5), MOR is the modulus of rupture (MPa), P_{max} is the maximum bending load (N), L is the span (mm), w is the width (mm), and t is the thickness (mm) of the specimen.

2.6.3. Internal Bond Strength

The internal bond strength is a measure of cohesion or the ability of the bioboard to withstand tensile forces. This is determined through a tensile strength test to evaluate the maximum load that the board can withstand before it ruptures. The internal bond strength was determined using the tensile strength perpendicular to the surface, as described in ASTMD1037-06a standard test methods [36]. Test samples of 50 mm square were obtained from the finished boards and utilized in the tests. The test specimen is loaded in a direction perpendicular to the plane of the board during the test using a universal testing machine

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(Instron Machine, Series 3360, Instron, MA, USA). The tensile strength is calculated using Equation (6).

$$IB = \frac{P_{max}}{wL} \quad (6)$$

From Equation (6), IB is the internal bond strength (MPa), P_{max} is the maximum tensile load (N), w is the width of the specimen (mm), and t is the thickness of the specimen (mm).

2.7. Statistical Analysis of Responses

The analysis of responses from the experimental design was conducted in Minitab statistical software (Minitab 21.2). Analysis of Variance (ANOVA) was used to identify the significant parameters. Empirical equations were developed to predict physical and mechanical properties using multiple regression analysis. To improve the prediction and usefulness of the empirical analysis and models, backward elimination was utilized to reduce the model by removing the least significant terms.

Pearson correlation was used to understand the correlation between the responses. The strength of the correlation was determined by estimating Pearson's correlation coefficient (r). In addition to this, a scatter plot with trend lines was used to determine the relationship of the responses using density as a reference.

2.8. Scanning Electron Microscopy

The scanning electron microscope utilizes a concentrated beam of high-energy electrons to produce different signals at the surfaces of solid objects. The signals provide information on the crystalline structure, orientation, chemical composition, and exterior morphology (texture) of the sample. In this study, micrographs were generated using a scanning electron microscope (Phenom ProX Desktop SEM, Thermo-Fisher, Waltham, MA, USA). The specimens were sputter-coated with a thin layer of gold to improve surface conductivity and enhance image quality. The coated samples were imaged using the scanning electron microscope with an accelerating voltage of 15 kV at various magnifications (8000×–10,000×). The micrographs were used to study the morphology of the bioboards and to obtain information about their binding mechanism.

3. Results and Discussion

3.1. Physical Properties of Bioboards

3.1.1. Density of Bioboards

The density of a bioboard is a crucial factor to consider because it determines the application of the board. The average density of bioboards produced from corn stover is presented in Table 1, and it ranges between 669.9 and 986.4 kg/m^3. From the study of Youngquist et al. [37], the medium-density fibreboards have densities between 64 and 800 kg/m^3, whilst the density of medium-density hardboard ranged from 500 to 800 kg/m^3. In addition, the insulating boards had densities ranging between 160 and 500 kg/m^3. It can be observed that the average densities obtained for the various treatments for the bioboard fell within the range of those for medium-density fibreboards and medium-density hardboards. Similarly, according to the American National Standards Institute (ANSI A208.1-1999) [38], the bioboards fall within the ranges of particleboard grades classified as high-density (above 800 kg/m^3) and medium-density (between 640 and 800 kg/m^3). The density of the bioboards obtained from corncobs by Orisaleye et al. [16] and sawdust by Orisaleye et al. [17] fell within the same range.

Table 1. Experimental design for the production of bioboard and average responses/characteristics of the bioboards.

Run	Variables				Average Physical Properties			Average Mechanical Properties		
	P (MPa)	T (°C)	θ (min)	S (mm)	ρ (kg/m^3)	WA (%)	TS (%)	MOE (MPa)	MOR (MPa)	IB (MPa)
1	15	100	5	6	874 ± 30	171 ± 11	421 ± 25	52.8 ± 8.4	0.59 ± 0.04	1.16 ± 0.07
2	9	100	5	3	669 ± 45	165 ± 6	131 ± 9	85.4 ± 5.9	0.15 ± 0.03	1.02 ± 0.07
3	9	150	5	6	986 ± 8	186 ± 14	453 ± 45	54. 4 ± 3.2	0.55 ± 0.05	1.12 ± 0.14
4	15	150	5	3	797 ± 54	170 ± 4	171 ± 8	23.4 ± 6.5	0.37 ± 0.03	0.77 ± 0.06
5	15	100	10	3	787 ± 54	169 ± 7	218 ± 16	13.3 ± 2.6	0.36 ± 0.02	0.43 ± 0.06
6	9	150	10	3	840 ± 42	186 ± 13	176 ± 13	48.2 ± 3.3	0.42 ± 0.17	0.95 ± 0.05
7	15	150	10	6	950 ± 14	209 ± 13	430 ± 11	85.6 ± 5.0	0.84 ± 0.06	1.17 ± 0.18
8	9	100	10	6	776 ± 30	237 ± 12	254 ± 17	50.6 ± 3.5	0.57 ± 0.11	1.03 ± 0.15

The ANOVA for the density of the corn stover bioboards is presented in Table 2. From the ANOVA in Table 2, the temperature and the particle size were found to be statistically significant on the density of the bioboards from the corn stalks. Similarly, the interaction between pressure and temperature was also significant for the bioboards' density. The standardized effects of the terms in the ANOVA are shown in the Pareto chart in Figure 3, which indicates that particle size had the greatest effect on corn stover bioboard density. This can be attributed to the packing of corn stover fibre and contact mechanics during the board formation under pressure. When the particle size is smaller, it increases the surface area, reduces the inter-particle voids, and enhances more contact points between the fibres. This allows the redistribution of softened lignin under hot pressing to facilitate a more closely packed board structure. Conversely, large particles create structural discontinuities and limit the degree of densification.

Table 2. ANOVA for the density of bioboards from corn stover.

Term	Effect	Coef	SE Coef	*t*-Value	*p*-Value	VIF
Constant		834.88	7.88	105.94	0.000	
P	34.25	17.13	7.88	2.17	0.118	1.00
T	116.75	58.37	7.88	7.41	0.005	1.00
S	123.25	61.62	7.88	7.82	0.004	1.00
P × T	−73.75	−36.87	7.88	−4.68	0.018	1.00

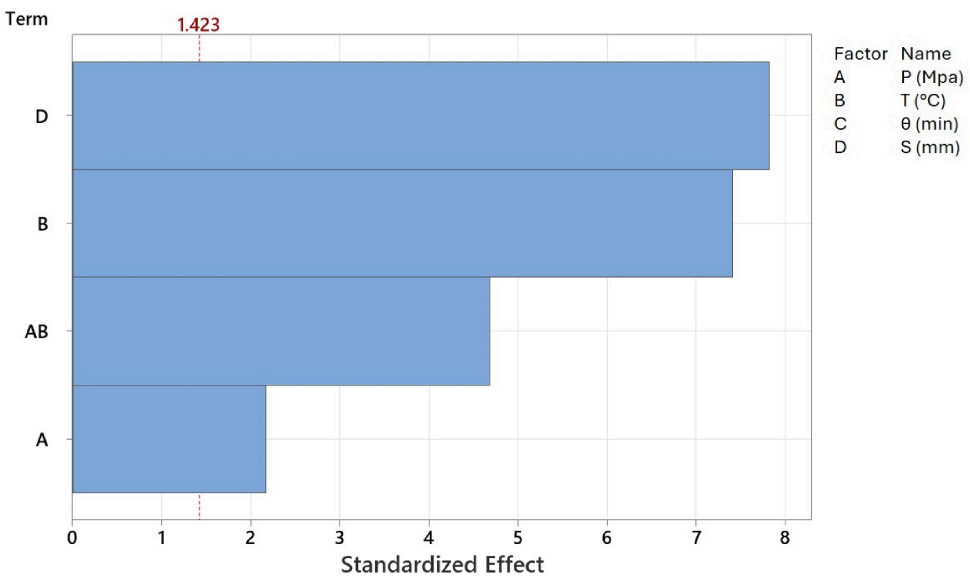


Figure 3. Pareto chart of standardized effects for density of bioboards from corn stover.

In line with the findings from this study, Orisaleye et al. [16] found that the temperature and particle size were statistically significant. Contrary to this study, however, Orisaleye et al. [16] found that pressure and pressing time were significant for the density of corncob bioboards, but particle size was significant and had the largest effect on the density of corncob bioboards. Also, similar to this study, Orisaleye et al. [17] found that temperature is significant to the density of sawdust bioboards, but also found pressure to be significant, which is contrary to the current study.

The empirical model that describes the relationship between density and the variables is given in Equation (7). The model has a coefficient of determination (R^2) of 97.94% and an adjusted R^2 of 95.19%. Figure 4 shows that the empirical model closely matches the experimental observations.

$$P = -448 + 67.2\,P + 8.23\,T + 41.08\,S - 0.492\,P \times\,T \quad (7)$$

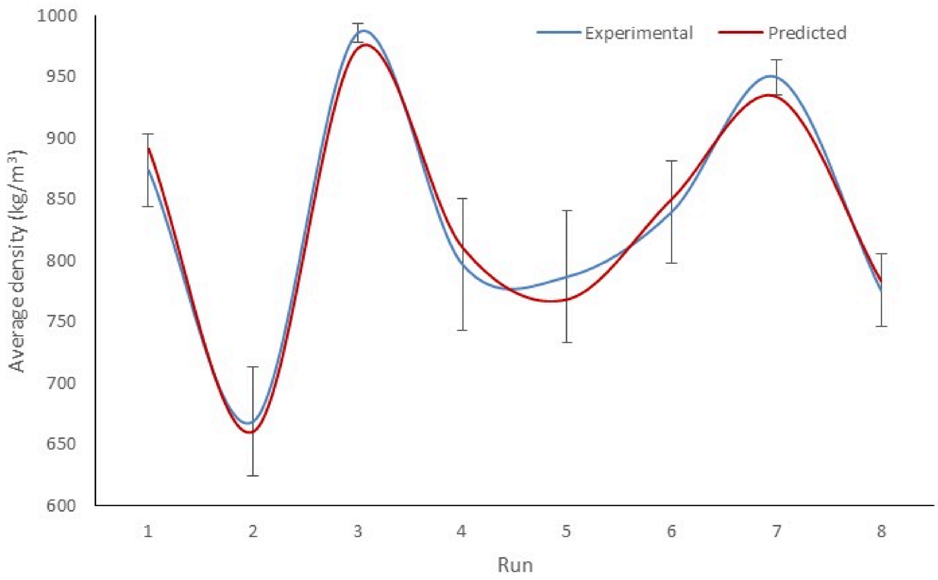


Figure 4. Comparison of predicted density with the observed values of the average density of corn stover bioboards.

3.1.2. Water Absorption of Bioboards

The water absorption property of bioboards is a major factor in effectively evaluating their capacity to absorb moisture from the surrounding environment. Water absorption also impacts the dimensional stability of the bioboards. From Table 1, the water resistance of all bioboards produced with the different treatments was very high, with water absorption ranging from 165 to 237%. This may indicate the presence of numerous pores within the bioboards or the insufficient resistance to moisture of the internal binding components of biomass. The presence of pores, which is established through investigation of SEM images, shows insufficient matrix formation and bonding between the fibres. This results in a discontinuous structure that facilitates the penetration of moisture into the interior of the boards. Mechanistically, high water absorption is governed by both structural and chemical factors. The presence of the pores, which are interconnected within the board structure, serves as capillary pathways allowing the ingress of water. The high hemicellulose in corn stover contains abundant hydroxyl groups, which promote hydrogen bonding with water molecules. The result of this is the high hygroscopicity of the corn stover boards. Based on this, there is a need for further processing of the fibres to ensure that the lignin content within the fibre is more readily available for binding and matrix formation, which would ensure water-resistant boards.

The study by Kurokochi and Sato [39] also reported high water absorption for bioboards produced from rice straw, noting that water absorption was slightly improved when rice straw was steam treated. Similarly, Zuraida et al. [40] found that the water absorption of binderless boards reached 171.4% for coconut husk boards and 142.3% for sugarcane bagasse boards. However, corn stover has been reported to have more hemicellulose content (26–31%) than rice straw (23–28%) and sugarcane bagasse (19–24%) [41]. Although lignin is hydrophobic, the higher hemicellulose content, being hygroscopic, might have contributed to the higher moisture absorption experienced by the bioboards made from corn stover. Water absorption of thermo-compressed sugarcane bagasse has been reported by Cavailles et al. [42] to range between 21% and 240%. For the bioboards produced from corn stover, the water absorption can be reduced by treating the fibres to reduce the hemicellulose content, consequently decreasing the hydroxyl groups, to reduce the water affinity of the boards. Moreover, lignin and other natural binding components can be extracted from other lignocellulosic sources and used to strengthen the corn stover bioboards. Higher processing temperatures and higher pressing times could also be used, noting, however, that charring occurs as the pressing temperature reaches 200 °C. Exploitation of chemical pretreatment like mild acid hydrolysis and steam explosion could be beneficial as these could improve the availability of the lignin for binding whilst modifying the hemicellulose content of the fibres.

The ANOVA for the water absorption of corn stover bioboards is presented in Table 3. The table shows that the temperature and particle size have a significant influence on the water absorption of the bioboard at a lower level of confidence ($p < 0.01$). The Pareto chart in Figure 5 implies that particle size had the largest effect on the water absorption, followed by pressing time. The result obtained agrees with the findings of Cavailles et al. [42] on the importance of time but disagrees on the influence of temperature.

Table 3. ANOVA for the water absorption of bioboard from corn stover.

Term	Effect	Coef	SE Coef	t-Value	p-Value	VIF
Constant		186.63	4.13	45.16	0.000	
P	−13.75	−6.88	4.13	−1.66	0.238	1.00
T	2.25	1.12	4.13	0.27	0.811	1.00
θ	27.25	13.62	4.13	3.30	0.081	1.00
S	28.25	14.13	4.13	3.42	0.076	1.00
P × T	17.25	8.62	4.13	2.09	0.172	1.00

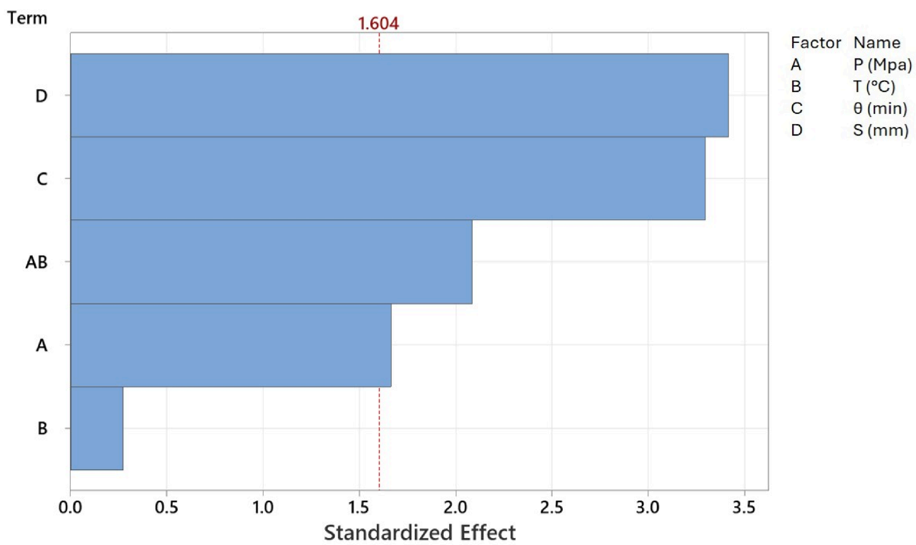


Figure 5. Pareto chart of standardized effects for the water absorption of corn stover bioboards.

Equation (8) presents the empirical model relating water absorption to the variables in the ANOVA. The model has an R^2 of 93.70% and an adjusted R^2 of 77.95%. Figure 6 shows that the empirical model closely matches the experimental observations.

$$WA = 297.8 - 16.67\,P - 1.335\,T + 5.45\,\theta + 9.42\,S + 0.1150\,P \times T \quad (8)$$

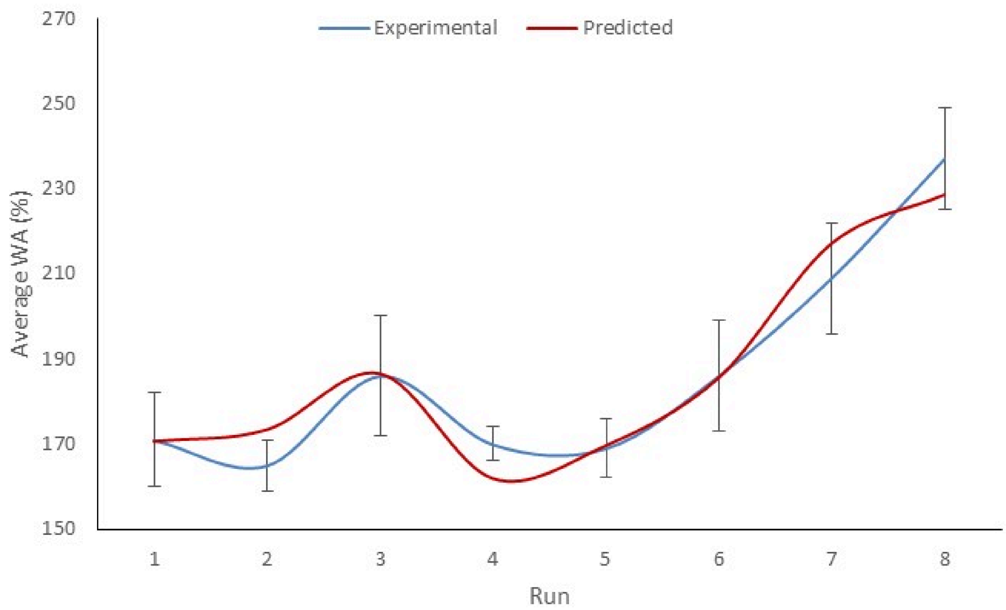


Figure 6. Comparison of predicted water absorption with the observed values of the average water absorption of corn stover bioboards.

3.1.3. Thickness Swelling of Bioboards

Thickness swelling is an important characteristic for evaluating the performance of bioboards, which refers to the dimensional changes that occur when the board absorbs moisture. It determines the board's stability, durability, and overall functionality in various applications. From Table 1, the thickness swelling is large and ranges from 131 to 453%. As noted by Zuraida et al. [40], a high degree of thickness swelling may be due to the internal structure, hygroscopicity or hemicellulose characteristics of the fibres used in the production of the bioboards. According to the study by Zuraida et al. [40], coconut husk and sugarcane bagasse had thickness swelling of 77.6% and 95.4%, respectively.

As previously noted from the observations for the water absorption, the thickness swelling occurs due to insufficient availability of lignin for the binding of the fibre to create a water-resistant structure. This has resulted in a porous structure with poor matrix formation that compromises the integrity of the board when exposed to moisture. In addition to this, the high presence of hygroscopic hemicellulose causes water absorption and penetration into the cell walls. The thickness swelling can be attributed to the disruption of the bonding between fibres when moisture has been absorbed. As water penetrates the board structure, the hydrogen bonds between the cellulose and hemicellulose chains weaken and result in fibre separation and board disintegration. When lignin has been insufficiently distributed, there is a pronounced effect due to the absence of a continuous hydrophobic matrix, resulting in dimensional instability upon moisture absorption. The modification of the hemicellulose constituents will be beneficial to the improvement of the thickness swelling. In addition, the supplementation of the binding using external binding materials from natural origin could improve the properties of the corn stover bioboards.

The ANOVA for the thickness swelling of corn stover boards is presented in Table 4. It is observed that the particle size is the only term that is statistically significant ($p < 0.05$)

to the thickness swelling of the corn stover bioboard. The Pareto chart in Figure 7 also shows that the particle has the largest effect on the corn stover bioboard. The strong influence of the particle size on the thickness swelling is consistent with the findings for the water absorption.

Table 4. ANOVA for the thickness swelling of bioboard from corn stover.

Term	Effect	Coef	SE Coef	*t*-Value	*p*-Value	VIF
Constant		281.8	17.3	16.27	0.001	
P	56.5	28.3	17.3	1.63	0.201	1.00
T	51.5	25.7	17.3	−1.49	0.234	1.00
S	215.5	107.7	17.3	6.22	0.008	1.00
P × T	−70.5	−35.2	17.3	−2.04	0.135	1.00

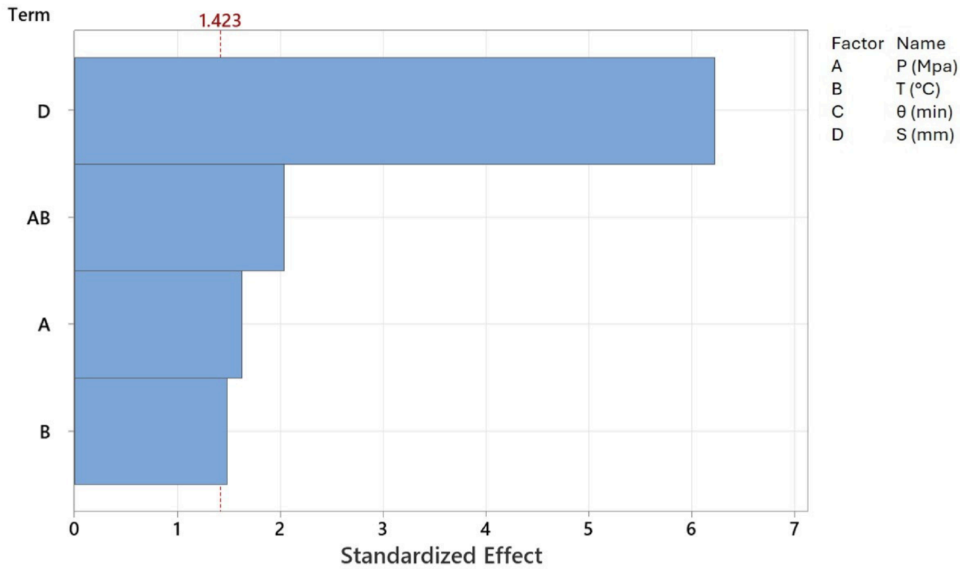


Figure 7. Pareto chart of standardized effects for thickness swelling of corn stover bioboards.

The relationship between the thickness swelling and the terms presented in the ANOVA is expressed in Equation (9) and has R^2 and adjusted R^2 values of 94.09% and 86.21%, respectively. The comparison of the observed average thickness swelling of the bioboards with the predicted values is shown in Figure 8. It is seen that the equation gives a good prediction of the thickness swelling.

$$TS = -988 + 68.2\,P + 6.67\,T + 71.8\,S - 0.470\,P \times T \quad (9)$$

3.2. Mechanical Properties of Bioboards

3.2.1. Modulus of Elasticity

The modulus of elasticity of the bioboards ranged between 13.3 and 85.6 Mpa, as shown in Table 1. The modulus of elasticity of corn stover boards was generally higher than that obtained for corncob bioboards by Orisaleye et al. [16], where the maximum modulus of elasticity of corncob boards was 34.10 MPa. From the study on sawdust bioboards by Orisaleye et al. [17], however, the modulus of elasticity reached up to 100.4 MPa. The modulus of elasticity obtained for the corn stover boards is less than the minimum value of 1550 MPa specified by ANSI A208.1-1999 [38] for particle boards for general usage and furniture.

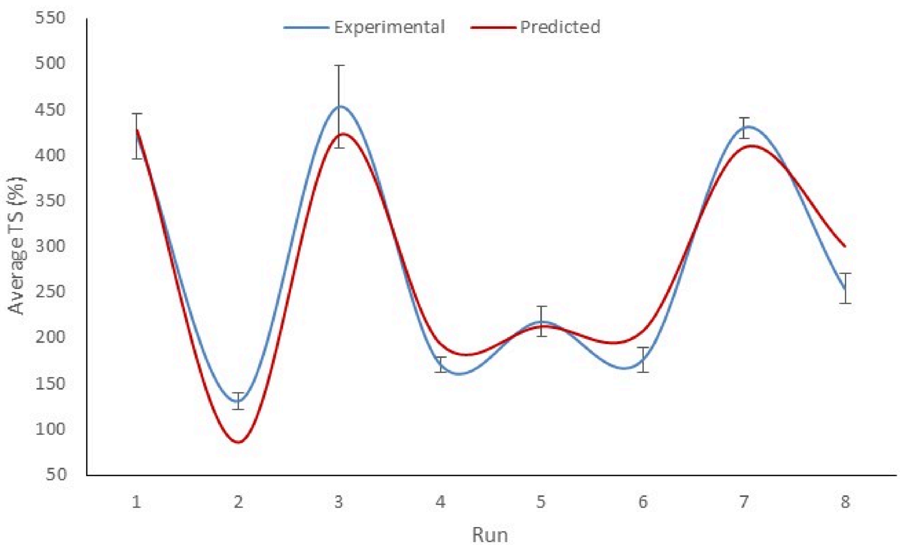


Figure 8. Comparison of predicted thickness swelling with the observed values of the average thickness swelling of corn stover bioboards.

The modulus of elasticity of the corn stover bioboards could have been influenced by a range of factors, including the poor adhesion of the fibres and large voids within the produced boards. As previously noted, this can be resolved by supplementing the bonding with external binding components rather than relying on the internal binding constituents that have proven to be insufficient. In addition, further processing of the fibres and increasing pressing times could lead to improved fibre softening of the fibres, whilst higher pressures could ensure that the particles are forced closer together to enhance the binding of the particles.

The low modulus of elasticity observed in the corn stover bioboards can be attributed to several factors, including inadequate inter-fibre bonding and the presence of large voids within the structure. As observed from the SEM analysis, the discontinuous matrix and poor consolidation of fibres result in inefficient load transfer across the board, thereby reducing stiffness. The low modulus of elasticity derives from the inefficient stress transfer within the composite structure. Boards with properly bonded structures transmit load through a continuous matrix-fibre network; however, the boards produced from corn stover have a discontinuous lignin phase, demonstrated by the presence of voids. This interruption of the continuous structure of the matrix prevents uniform stress distribution across the board cross-section but causes deformation in localized regions within the board. Although the use of fibres ensures cross-linking of the particles, this bonding mechanism by itself is not sufficient to ensure sufficient flexural strength of the boards. Similar observations can be attributed to inadequate lignin flow in binderless boards, resulting in insufficient consolidation of the particles.

The ANOVA for the modulus of elasticity of the corn stover boards is presented in Table 5, where it is seen that the particle size and the interaction between the pressure and the particle size significantly influence the modulus of elasticity at a confidence level of 90% ($p < 0.1$). From the study of Orisaleye et al. [35], only the particle size was also observed to be significant to the modulus of elasticity of corncob boards. Contrary to the findings of this study, Orisaleye et al. [17] found that the pressure and temperature were statistically significant for the modulus of elasticity of sawdust boards. Particle size was the factor that had the highest effect on the modulus of elasticity of the corn stover boards, as shown in Figure 9.

Table 5. ANOVA for the modulus of elasticity of bioboard from corn stover.

Term	Effect	Coef	SE Coef	t-Value	p-Value	VIF
Constant		51.71	6.34	8.15	0.001	
P	−15.88	−7.94	6.34	−1.25	0.279	1.00
S	18.27	9.14	6.34	1.44	0.223	1.00
P × S	32.57	16.29	6.34	2.57	0.062	1.00

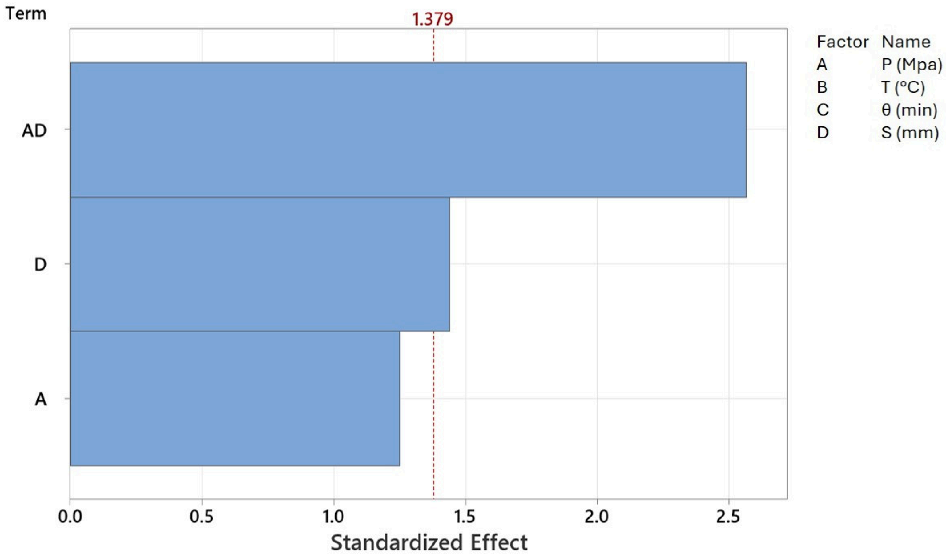


Figure 9. Pareto chart of standardized effects for modulus of elasticity of corn stover bioboards.

The empirical model for the modulus of elasticity of corn stover boards is expressed in Equation (10), and it has R^2 and adjusted R^2 values of 71.89 and 50.81%, respectively. The predicted modulus of elasticity from the equation is compared with the observed average values in Figure 10. The model predicts the modulus of elasticity, but with some deviation from the observed values due to the limited number of significant terms.

$$\text{MOE} = 251.5 - 18.93\ \text{P} - 37.3\ \text{S} + 3.62\ \text{P} \times \text{S} \tag{10}$$

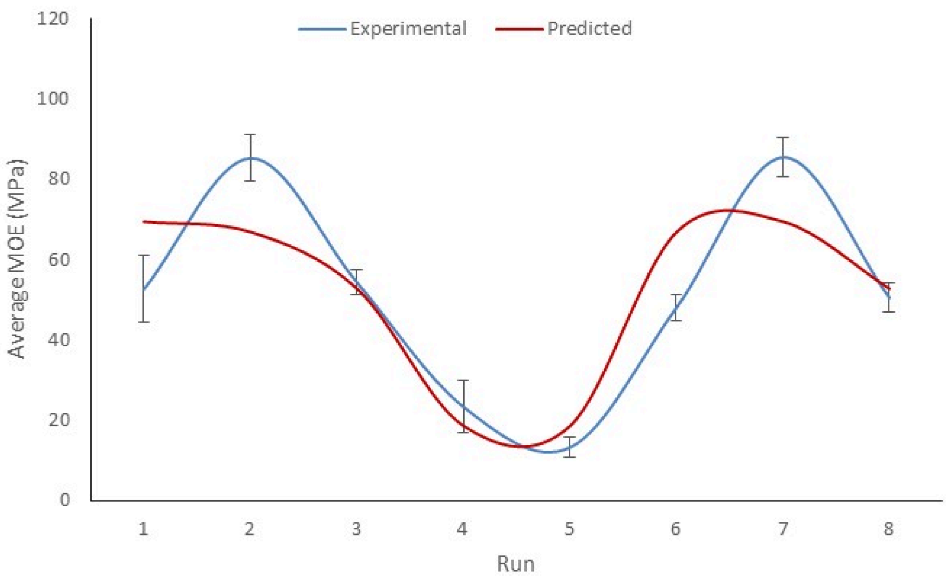


Figure 10. Comparison of predicted modulus of elasticity with the observed values of the average modulus of elasticity of corn stover bioboards.

3.2.2. Modulus of Rupture of Bioboards

The modulus of rupture is one of the mechanical properties that determines the applicability of the bioboard. From Table 1, the modulus of rupture for the corn stover bioboards varies between 0.149 and 0.835 MPa. Considering the ANSI A208.1-1999 [38], the modulus of rupture should attain a value of 10 MPa for application in interior fitments. The modulus of rupture for the corn stover bioboards is less than the specified recommendation by ANSI A208.1-1999 [33]. The modulus of rupture of the corn stover bioboards, however, falls within the same range as obtained by Orisaleye et al. [16] for corncob boards. The modulus of rupture obtained for sawdust bioboards by Orisaleye et al. [17] is also comparable to values obtained for corn stover boards. As previously noted for the modulus of elasticity, the low modulus of rupture implies low load-bearing capacity that could be improved by improving processing parameters, modifying the biomass fibres, and adding external binders. This highlights that, although internal bonding is sufficient at a local level, the presence of voids and discontinuities prevents the formation of a continuous load-bearing structure, thereby limiting bending performance. This indicates that failure of the board is due to premature crack formation initiated at the voids and interfaces that have been weakly bonded. During bending, there is a concentration of stresses at these regions, which leads to early fracture, limiting the ability of the boards to carry full load.

The ANOVA for the modulus of rupture of the corn stover boards is presented in Table 6. It is observed that all factors, including pressure, temperature, particle size, and pressing time, are significant to the modulus of rupture ($p < 0.05$). The Pareto chart in Figure 11 shows that the particle size has the largest effect on the modulus of rupture of corn stover boards, followed by pressing time, temperature, and pressure, in that order. The study of Orisaleye et al. [17] also showed that the pressing time can significantly influence the modulus of rupture of sawdust boards. Vitrone et al. [1] noted that the pressing time at a given temperature was a significant factor in determining the modulus of rupture of binderless boards. Also, in line with the findings of this study on corn stover boards, Orisaleye et al. [16] found that pressure, temperature, pressing time, and particle size were significant in determining the modulus of rupture of corncob boards.

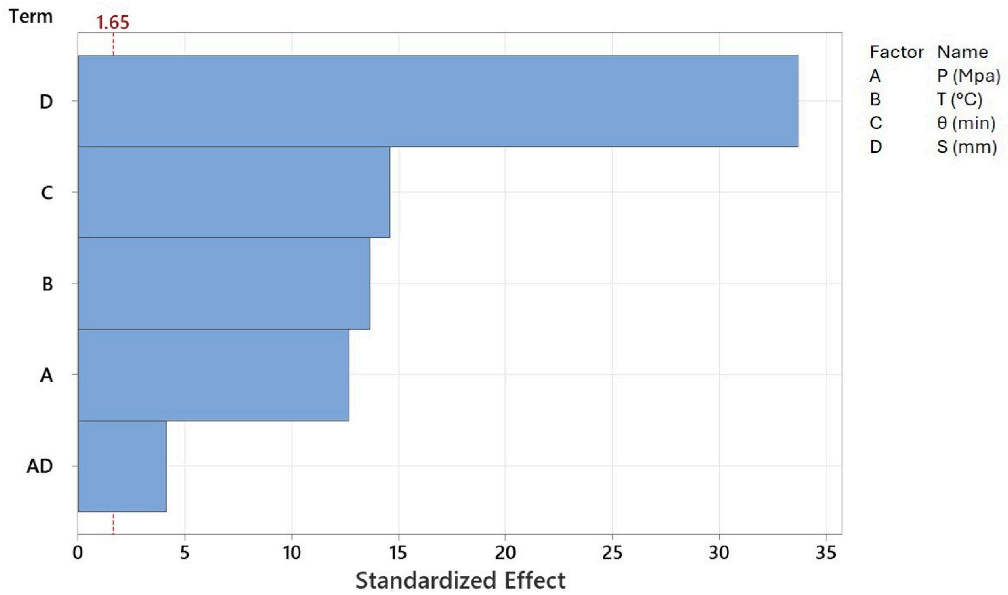


Figure 11. Pareto chart of standardized effects for modulus of rupture of corn stover bioboards.

Table 6. ANOVA for the modulus of rupture of bioboard from corn stover.

Term	Effect	Coef	SE Coef	*t*-Value	*p*-Value	VIF
Constant		0.47925	0.00460	104.9	0.000	
P	0.11650	0.05825	0.00460	12.66	0.006	1.00
T	0.12550	0.06275	0.00460	13.64	0.005	1.00
θ	0.13400	0.06700	0.00460	14.57	0.005	1.00
S	0.31000	0.15500	0.00460	33.70	0.001	1.00
P × S	0.03800	0.01900	0.00460	4.13	0.054	1.00

The empirical model that describes the relationship with the terms in the ANOVA is expressed in Equation (11). The empirical model has R^2 and adjusted R^2 values of 99.88 and 99.59%, respectively. The values obtained from the empirical model compared with the observed experimental values for the average modulus of rupture are shown in Figure 12. It is seen that the empirical model accurately describes the modulus of rupture with very high precision, as indicated by the coefficients of regression.

$$\mathrm{MOR} = -0.5055 + 0.00042\,\mathrm{P} + 0.002510\,\mathrm{T} + 0.02680\,\theta + 0.0527\,\mathrm{S} + 0.00422\,\mathrm{P} \times \mathrm{S} \quad (11)$$

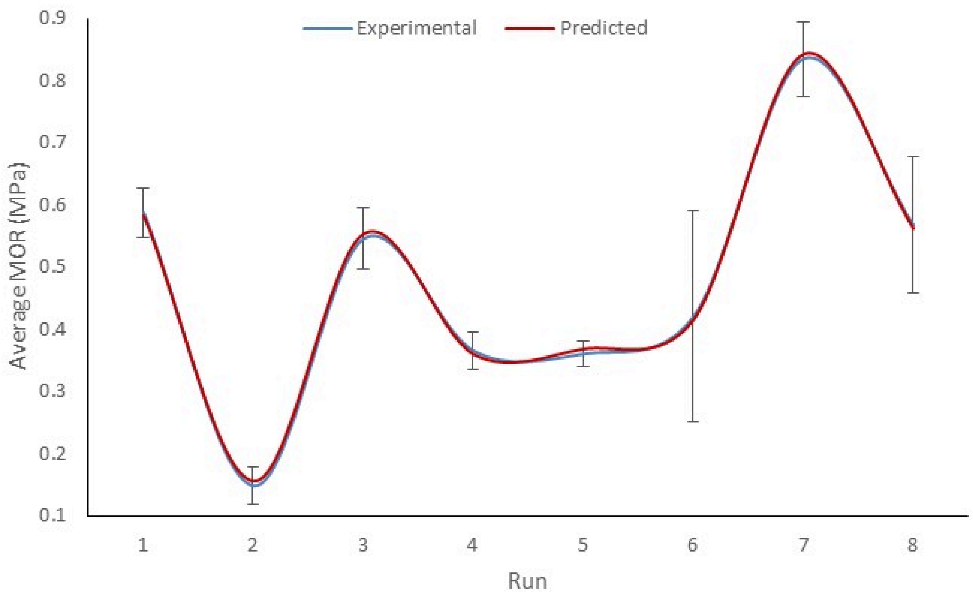


Figure 12. Comparison of predicted modulus of rupture with the observed values of the average modulus of rupture of corn stover bioboards.

3.2.3. Internal Bond Strength of Bioboards

The internal bond strength determines whether the particles forming the bioboard have sufficient cohesion to resist tensile forces. It is an indicator of the internal adhesion between the lignin matrix and the fibre within the bioboard. The average internal bond strength of the corn stover boards varies between 0.43 and 1.17 MPa across different bioboard treatments. The internal bond strength falls below the specification of ANSI 208.1-1999 [38] and EN 312 [43]. ANSI 208.1-1999 [38] specifies an internal bond strength of 0.5 MPa, whilst EN 312 [43] specifies 0.4 MPa. The internal bond strength obtained for the corn stover boards was also higher than that observed by Orisaleye et al. [16,17] for corncob boards and sawdust bioboards. This may be because the particles had longer fibres that could enhance internal bonding through cross-linking rather than particle-to-particle bonding in the sawdust and corncob bioboards.

Despite the relatively high IB values, the boards exhibited significantly low modulus of elasticity and modulus of rupture, highlighting a disparity between local bonding and global mechanical performance. The cross-linking of the particles also explains the observed disparity between relatively high internal bond strength and low bending properties, as localized fibre adhesion does not translate into a continuous load-bearing network under flexure. The discontinuity resulting from the presence of voids within the boards, observed from scanning electron microscopy, due to insufficient matrix formation for binding, has resulted in the low moduli of elasticity and rigidity. However, the fibre entanglement and mechanical interlocking give rise to local adhesion, resulting in higher tensile strength. The relatively high internal bond strength indicates that localized adhesion mechanisms such as fibre entanglement and mechanical interlocking are effective at resisting tensile separation.

The values obtained for the internal bond strength of the corn stover boards were also higher than those reported by Zuraida et al. [40] for rattan, kenaf, coconut husk and sugarcane bagasse, and Kurokochi and Sato [39] for rice straw. Khoo et al. [12], however, obtained internal bond strength reaching 2.51 MPa for bioboards produced using mushroom mycelium and substrate waste.

From Table 7, the particle size is marginally significant for the internal bond strength of corn stover boards at a 90% confidence level ($p < 0.1$). In addition, the interaction between pressure and particle size is also statistically significant. The Pareto chart in Figure 13 shows that the particle size has the highest effect on the internal bond strength of the corn stover bioboard. According to the study by Orisaleye et al. [17], pressure and temperature were found to significantly influence the internal bond strength of sawdust bioboards. Similar to the observation for the corn stover bioboards, Orisaleye et al. [16] also found that the particle size was significant and had the highest effect on the internal bond strength of corncob bioboards.

Table 7. ANOVA for the internal bonding of bioboard from corn stover.

Term	Effect	Coef	SE Coef	*t*-Value	*p*-Value	VIF
Constant		0.9563	0.0448	21.32	0.000	
P	−0.1475	−0.0738	0.0448	−1.64	0.175	1.00
S	0.3275	0.1638	0.0448	3.65	0.022	1.00
P × S	0.2375	0.1187	0.0448	2.65	0.057	1.00

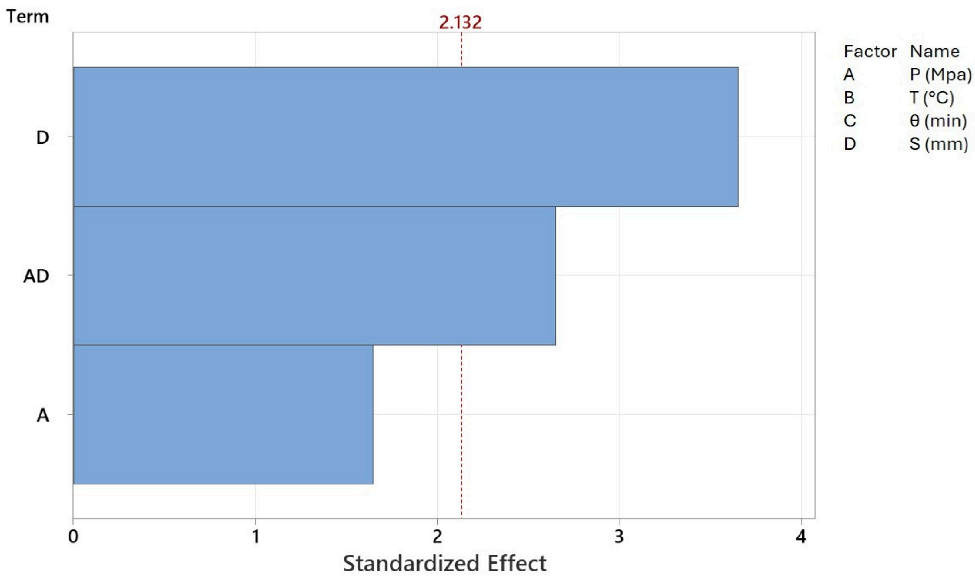


Figure 13. Pareto chart of standardized effects for internal bond strength of corn stover bioboards.

The internal bond strength (IB) of the corn stover bioboards can be predicted using the empirical model in Equation (12). The empirical model has coefficients of regression R^2 and adjusted R^2 as 85.21 and 74.12%, respectively. The model has been compared with the experimental observations of the average internal bond strength in Figure 14. It is seen that the empirical model predicts the internal bond strength closely.

$$IB = 2.185 - 0.1433\,P - 0.207\,S + 0.02639\,P \times S \quad (12)$$

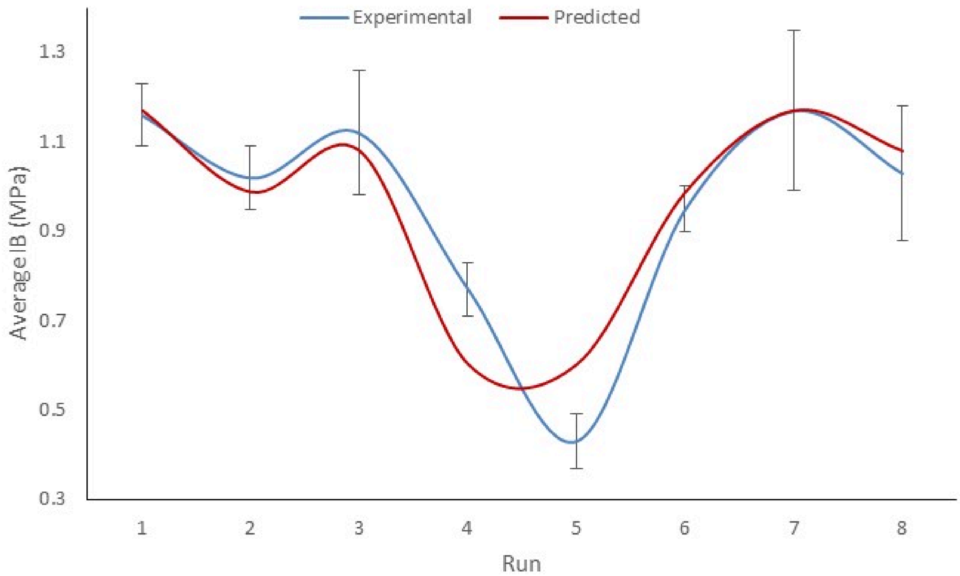


Figure 14. Comparison of predicted internal bond strength with the observed values of the average internal bond strength of corn stover bioboards.

3.3. Correlation of Responses

Using the Pearson correlation, the degree of correlation between the responses is shown in Table 8. From the table, it is seen that the MOR has a high correlation with the density, whereas other responses, except the TS, have weak correlations, although positive, with the density. The correlation of the TS with the density may be explained by the loss of the bonding properties of the boards with the absorption of moisture. High-density boards imply that there has been a high compaction, and the expansion resulting from the loss of bonding is expected to be higher with denser boards compared to less dense boards. Similarly, the poor correlation of the density with the WA shows that increased compaction limits the penetration of moisture into the boards. Figure 15 shows a scatter plot of normalized values of the responses against the density with trendlines to visualize the trends for each response. The figure shows that all the responses are positively correlated with the density, but with different strengths of correlation. The plot further shows that the MOR and TS have a high correlation with the density, whilst the WA and MOE have the weakest correlation.

Table 8. Pearson's correlation coefficient for responses.

Response	Density	WA	TS	MOE	MOR	IB
Density	1.000					
WA	0.259	1.000				
TS	0.845	0.282	1.000			
MOE	0.132	0.278	0.289	1.000		
MOR	0.765	0.609	0.763	0.257	1.000	
IB	0.431	0.408	0.552	0.771	0.476	1.000

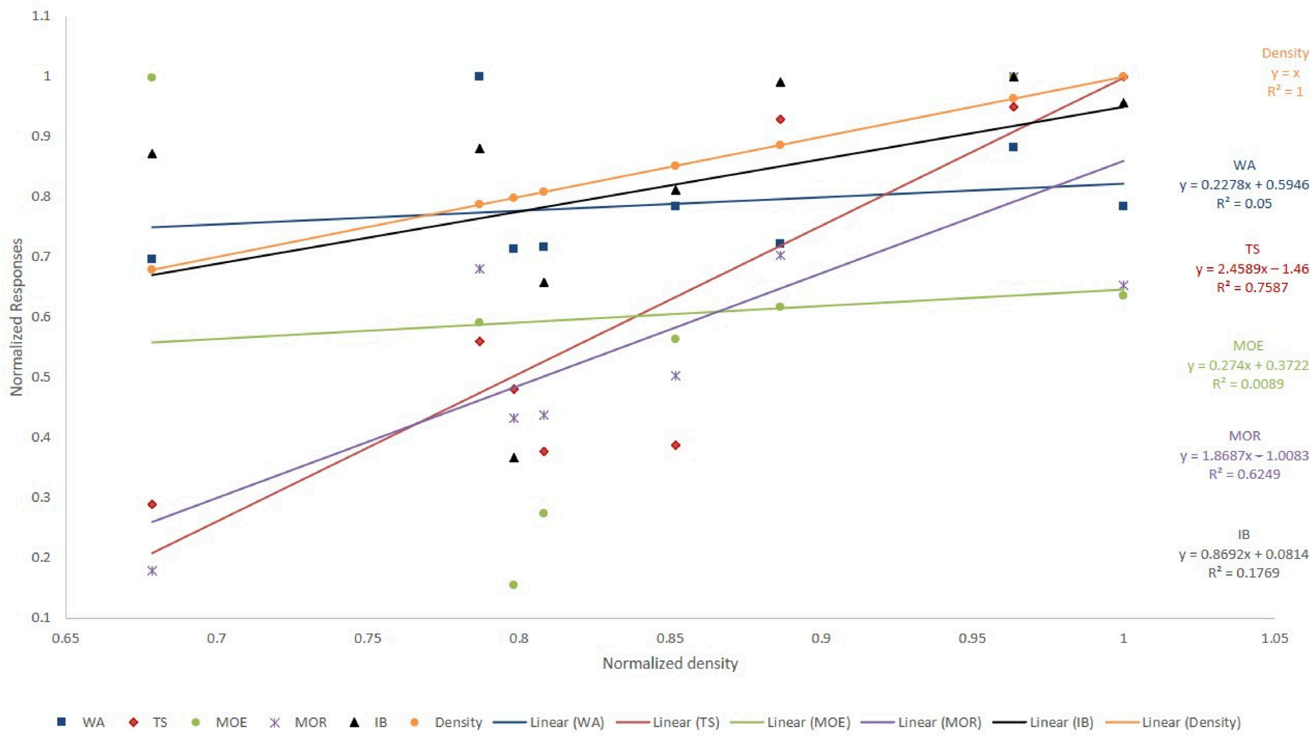


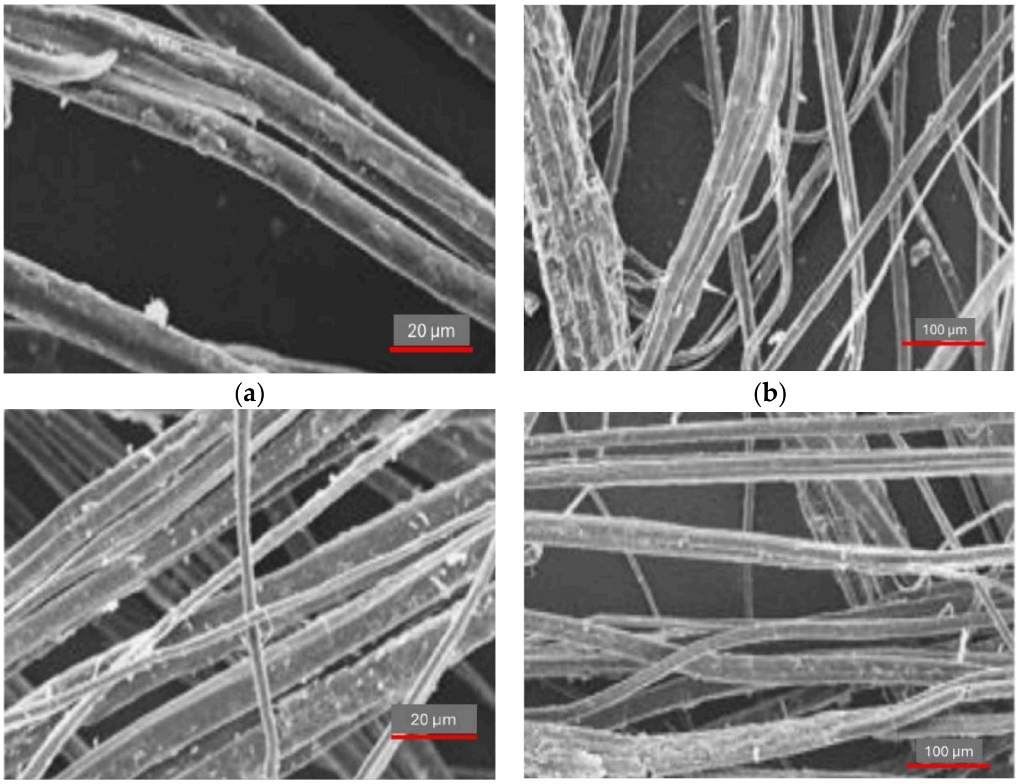
Figure 15. Scatter plot with trendline of normalized responses (density, WA, TS, MOE, MOR and IB) against density of the boards.

3.4. Scanning Electron Microscope Analysis

The micrographs from the scanning electron microscope for the bioboards manufactured under different conditions are presented in Figure 16. Figure 16a,b show the SEM for the boards produced with corn stover fibre obtained from milling with the 6 mm mesh at 20 μm and 100 μm spatial resolution, respectively. Figure 16c,d show it for those produced with a milling mesh of 3 mm at 20 μm and 100 μm spatial resolution, respectively.

From the micrographs, it is observed that the binding mechanism employed is mechanical cross-linking of fibres and the use of natural binding constituents that coat the fibres. These combined binding mechanisms may have resulted in the higher internal bond strength of the boards compared to particulate bioboards [16,17]. The cross-linking of the fibres and adhesion of the particles show that the particles are rearranged within the mould under the application of pressure. The heating of the biomass fibres within the pressing mould causes the plasticisation and thermal softening of lignin, which coats the fibre particles when subject to pressure. This causes the inter-particle adhesion when the particles are forced together under pressure. However, the presence of voids shows that lignin does not sufficiently provide the required matrix to form high-strength and water-resistant boards. To improve the strength of the boards, the addition of external binding to supplement matrix formation could present substantial benefits.

From the micrographs, the boards made with the smaller particle-sized fibres are denser than those made from the larger particle sizes, indicating that the particle size is significant in the compaction of fibres to manufacture the boards. However, the figures show that there are large pores between the constituting fibre of the boards, which may have accounted for the high water absorption. The large pores indicate poor binding or insufficient binding material between the particles. This has resulted in the penetration of moisture through the pores of the boards and into the corn stover fibre. For the boards made with 3 mm particles, the fibres appear to have a more compact structure compared to the boards made with 6 mm particles, suggesting that a larger surface area may have resulted in better binding of the particles. This may have accounted for the slightly better thickness swelling observed with the boards made from smaller particles compared to larger particles. This shows that there is increased benefit to using smaller particles for the production of the bioboards, as reported by Orisaleye et al. [16] for corncob bioboards.



(c) (d)

Figure 16. Micrographs from scanning electron microscope for corn stover bioboards for 6 mm particle size at pressure of 15 MPa, pressing temperature of 150 °C and pressing time of 5 min [(**a**) 20 µm spatial resolution and (**b**) 100 µm spatial resolution]; and 3 mm particle size at pressure of 15 MPa, pressing temperature of 150 °C and pressing time of 5 min [(**c**) 20 µm spatial resolution and (**d**) 100 µm spatial resolution].

The SEM micrographs showing the existence of large voids suggest that additional treatment of the fibres may be needed to make their internal binding components readily available for binding. In addition to this, there may be a need for external bio-based binders to fill the voids to enhance the strength of the bioboards. Whilst the previous results show acceptable density, the discontinuity created within the boards through the existence of the voids, resulting in poor MOE and MOR, limits the application of the board as they cannot be used in load-bearing applications. Filling the voids using a binder creates a bridge between the particles and enhances the strength of the boards. The use of bio-based binders can be explored to improve these properties.

3.5. Practical Considerations for Production, Quality Control and Sustainability

Utilization of corn stover for bioboard production will result in decreased dependence on wood, thereby enhancing sustainability. There are several environmental and health benefits derived from eliminating formaldehyde and volatile organic compounds, avoiding the burning or decomposition of biomass, promoting circular bioeconomy, and reducing environmental footprint. To ensure sustainable production of commercial boards, several challenges that have been encountered and identified in various studies need to be addressed. These issues revolve around quality control and non-uniform parameters used in the production of bioboards. In this study, the heterogeneous nature of corn stover poses a major production issue, which causes variability in the fibre packing, lignin distribution, and bonding. These properties are essential to quality board production and could lead to variability in density, strength, and dimensional stability [44,45]. Processing conditions such as temperature and pressure need to be optimized as non-uniform factors result in localized voids and weak bonding. Moreover, from this study, it has been established that there is a need to utilize external binders to ensure that the boards are biodegradable and have the required quality.

Currently, the corn stover boards have limited load-bearing capacity but could be applied for insulation, packaging and other similar non-load-bearing applications. However, to further enhance the sustainable production of quality boards, the use of bio-based binders can be explored. In addition, the combination of corn stover with other materials, with a significant quantity of internal binding components, could be used to produce the boards. Maraveas [46] has suggested the incorporation of agro-waste such as moss fibres, starch, or cardboard to further enhance the properties of the boards. In addition to this, treatment using alkalis has been proposed to enhance the thermal features of the boards. Consideration of using waste plastics or polymeric content from municipal solid waste to develop composites when combined with the corn stover is an alternative that could be explored to extend circularity and avoid environmental degradation caused by plastic wastes and agro-wastes. There are several alternatives that can be explored that promote the circular economy whilst ensuring that boards of appropriate quality suitable for several applications are produced. Future life cycle analysis of bioboard production should assess energy use, emissions, and end-of-life. Overcoming variability, process control, scalability, and environmental performance is essential to bridge the gap between laboratory and commercial production. This ensures that the material meets both performance standards and sustainability goals.

4. Conclusions

This study investigated the influence of processing variables on the quality of binderless bioboards produced from corn stover. The hot pressing method was used to produce the bioboards with variations in pressure, temperature, and pressing time. The particle size was also varied using different mesh sizes in a combined chopping and milling machine. The physical properties investigated include density, water absorption and thickness swelling, whilst the mechanical properties include modulus of elasticity, modulus of rupture and internal bond strength. The density of the boards ranged between 669.9 kg/m^3 and 986.4 kg/m^3, the water absorption was between 165 and 237%, and the thickness swelling had values from 131 to 453%. The modulus of elasticity of the boards ranged between 13.3 and 85.6 MPa, whilst the modulus of rupture varied between 0.149 and 0.835 MPa. Also, the internal bond strength of the corn stover boards varied between 0.43 and 1.17 MPa. The density of the boards compared with medium-density fibreboards and medium-density hardboards, but the modulus of elasticity and modulus of rupture fell below recommended values by ANSI A208.1-1999. However, the internal bond strength surpassed the recommended value. The study observed that the water absorption and thickness swelling of the boards produced were high, indicating that the boards are best used in a dry environment. From the study, the significant parameters for each property were identified and empirical models were developed to predict the properties of the bioboard. It was shown that the particle size was an influential parameter for all the properties considered.

Corn stover demonstrates significant potential as a raw material for the development of bioboards. With the current parameters and level of processing, the corn stover boards are suitable for non-load-bearing applications and in a low-moisture environment. They could be used in buildings as interior decorative or wall panels, insulation panels, ceiling boards, and acoustic panels for sound absorption. The boards can also be used in low-load packaging applications as protective packaging boards and cushioning materials. In addition, the bioboards have the potential to be used for laminated panels where they are used as the core material in laminated panels being combined with stronger outer layers.

This study shows that the chemical composition of the fibre, the morphology and the limited thermal softening restrict the performance of binderless boards produced from corn stover. Further work needs to be conducted to improve its physical and mechanical properties to be used for load-bearing applications. These can be investigated through higher-temperature trials below the degradation temperature, varied pretreatment methods, or the addition of bio-based binders to the fibres. Advances made in improving the mechanical properties of the boards could strengthen the economic viability of bioproducts from corn stover within rural manufacturing systems. In addition to this, future work should also consider the influence of the manufacturing factors on fire resistance, biodegradability, thermal insulation, and sound insulation of the boards. Along with these, future work should consider identifying the optimum parameters for the production of high-quality bioboards using multi-objective optimization.

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