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Development of High-Performance Biocomposites from Kenaf, Bagasse, Hemp, and Softwood: Effects of Fiber pH Modification and Adhesive Selection on Structural Properties Correlated with FTIR Analysis

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Abstract

This study aims to develop high-performance biocomposites for structural applications using kenaf, bagasse, hemp, and softwood fibers bonded with phenol-formaldehyde (PF) and phenol-urea-formaldehyde (PUF) adhesives, commonly used in particleboard manufacturing. A simple, low-cost fiber treatment was applied by adjusting the fiber pH to 11 and 13 using a 33% NaOH solution, following standard protocols to enhance fiber–adhesive interaction. The effects of alkaline treatment on the chemical structure of bagasse, kenaf, and hemp fibers were investigated using Fourier Transform Infrared Spectroscopy (FTIR) and correlated with composite mechanical performance. PF and PUF were applied at 13% (*w*/*w*), while polymeric diphenylmethane diisocyanate (pMDI) at 5% (*w*/*w*) served as a control for untreated fibers. The fabricated panels were evaluated for mechanical properties; modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond strength (IB), and physical properties such as thickness swelling (TS) and water absorption (WA) after 24 h of immersion. FTIR analysis revealed that treatment at pH 11 increased the intensity of O–H, C–O–C, and C–O bands and led to the disappearance of the C=O band (~1700 cm^{-1}) in all fibers. Bagasse treated at pH 11 showed the most significant spectral changes and the highest IB values with both PF and PUF adhesives, followed by kenaf at pH 13, exceeding EN 312:6 (2010) standards for heavy-duty load-bearing panels in dry conditions. The highest MOE and MOR values were achieved with kenaf at pH 11, meeting EN 312:4 (2010) requirements, followed by bagasse, while softwood and hemp performed less favorably. In terms of thickness swelling, bagasse consistently outperformed all other fibers across pH levels and adhesives, followed by Kenaf and Hemp, surpassing even pMDI-based composites. These results suggest that high-pH treatment enhances the reactivity of PF and PUF adhesives by increasing the nucleophilic character of phenolic rings during polymerization. The performance differences among fibers are also attributed to variations in the aspect ratio and intrinsic structural properties influencing fiber–adhesive interactions under alkaline conditions. Overall, kenaf and bagasse fibers emerge as promising, sustainable alternatives to industrial softwood particles for structural particleboard production. PF and PUF adhesives offer cost-effective and less toxic options

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compared to pMDI, supporting their use in eco-friendly panel manufacturing. FTIR spectroscopy proved to be a powerful method for identifying structural changes caused by alkaline treatment and provided valuable insights into the resulting mechanical and physical performance of the biocomposites.

Keywords: natural fibers; synthetic adhesives; pH modification; FTIR; structural particleboard

1. Introduction

The shift toward reducing fossil fuel dependence calls for bio-based products and technologies rooted in sustainability, industrial ecology, eco-efficiency, and green chemistry [1]. Biomaterials, sourced wholly or partly from biomass, play a key role in this transition [2]. Particleboard, a major wood product, was valued at $21 billion globally in 2020, with a projected 4.4% annual growth over six years [3]. Its production mainly relies on resin and wood chips, which together account for over half of the total cost [4].

As global demand for wood materials increases, improving wood-use efficiency supports circular economy goals [5,6]. In Europe, environmental concerns and CO_2 reduction efforts challenge the wood panel industry to optimize lignocellulosic resources, enhance recycling, and explore alternative raw materials [7–9]. Competition from other sectors has further pushed the search for wood substitutes [10].

Using lignocellulosic agricultural wastes and natural fibers can lower production costs [11]. Particleboards, used in construction, furniture, and related sectors [12,13], increasingly incorporate natural fibers due to their low cost, renewability, and minimal energy use compared to synthetics [14]. Growing environmental awareness has also boosted interest in sustainable products [15], with fiber-based boards offering cost and ecological advantages [16].

Extensive research has addressed challenges in manufacturing particleboard from natural fibers. Hemp, kenaf, and bagasse are among the most studied biofibers as alternatives to synthetic fibers [17,18], commonly used with synthetic resins. Kenaf particleboard with UF, PF, and PMDI adhesives showed suitability for insulation, general purpose, and interior fitments, including furniture [19,20]. Kenaf was also effective for thermal and sound insulation [21].

Bagasse-based particleboards generally showed good physical and mechanical properties [4], though UF-bonded boards sometimes underperformed [22]. To improve quality, UF and PU were combined with wood particles [23,24], but concerns remain over UF toxicity and PU cost. Panels made from bagasse with UF and PF often failed to meet mechanical standards [25,26], and hot water-treated bagasse did not meet requirements for indoor dry-use panels [27]. Enhancements using alkali treatment or chemical modification, with added wood particles, were suggested to meet dry-condition standards [28,29].

Hemp, a fast-growing crop with strong sustainability credentials, is already used in thermal insulation [30]. Though UF-bonded hemp particleboards showed low mechanical strength and poor TS and WA, better results were obtained using PMDI and Soybean resins [31,32]. Mixing hemp with other fibers or wood particles has yielded boards with properties similar to industrial wood-based panels [33–40].

In general, the mechanical properties of boards produced from agricultural and wood-based fibers tend to be lower than those made from virgin wood fibers. Studies have shown that particleboards fabricated from untreated fibers often exhibit inferior mechanical properties due to the poor adhesion between fibers and adhesives. To address this challenge, the treatment of natural fibers is essential for achieving satisfactory mechanical performance [41]. The strength of these composites can be enhanced through surface modification, chemical treatment [42], and by optimizing the type and amount of adhesive used in the formulations.

Several studies have reported significant increases in mechanical properties when fibers were treated with alkali, silane, acetylation, or benzoylation [43]. A study on date palm fibers using Response Surface Methodology (RSM) evaluated several treatment parameters, including NaOH concentration, treatment time, and fiber diameter. The results revealed that, unlike fiber diameter, increases in NaOH concentration and treatment time had a significantly proportional impact on the mechanical properties of the fibers [44]. Although the use of high concentrations of these chemicals was found to increase tensile strength, flexural strength, and impact resistance, it may raise environmental and sustainability concerns that need to be addressed [45].

It is well known that polymers and fibers possess different chemical properties, which can promote strong interfacial adhesion, enabling effective stress transfer and uniform bond distribution across the interface [46]. Most studies have concluded that fiber surface treatment is necessary to enhance interfacial adhesion by removing impurities initially present on the outer surface of fibers and reducing the content of amorphous components such as hemicellulose, lignin, and waxes [47].

In order to analyze the chemical structure of natural fibers and detect the changes induced by alkali treatment, Fourier Transform Infrared Spectroscopy (FTIR) is recognized as an effective method for identifying the functional groups in these fibers and monitoring their response to chemical modifications. Several studies have reported that the broad absorption band around 3300–3400 cm^{-1}, associated with O–H stretching, often shifts or changes in intensity after alkali treatment, indicating alterations in hydrogen bonding and the removal of non-cellulosic materials [48,49]. Similarly, the C=O stretching bands near 1730–1740 cm^{-1}, attributed to hemicellulose and lignin, typically decrease or disappear after treatment, reflecting their removal [50,51].

The C–H stretching bands near 2900 cm^{-1} also reduce in intensity, signaling the loss of non-cellulosic components [51]. Absorption bands between 1000 and 1300 cm^{-1}, related to C–O–C and C–O stretching in cellulose and hemicellulose, shift after treatment, suggesting chemical structure changes [50,52]. These spectral modifications confirm the removal of hemicellulose and lignin, leading to increased cellulose content and enhanced fiber–matrix adhesion [51]. Improved surface roughness and reactivity promote stronger polymer bonding and better mechanical properties, such as higher tensile strength and stiffness [52].

Conventional adhesives for wood composites are based on four major synthetic thermosetting resins: phenol-formaldehyde (PF), urea formaldehyde (UF) melamine formaldehyde (MF), and polymeric diphenylmethane diisocyanate (pMDI). In comparison to traditional natural adhesives, synthetic adhesives are increasingly prevalent since they are more effective and less expensive. Among these adhesives, UF resins are mainly used in the manufacturing of particleboard and medium-density fiberboard (MDF) as it has good bonding properties and a short pressing time, and can be formulated for a wide range of curing temperature resulting in a faster production rate, lower energy consumption, and hence relatively low cost. The types of adhesives used for manufacturing PB in the European market are mainly UF (90–92%), MUF (6–7%), and pMDI (1–2%) [53]. However, UF adhesives have been categorized as a carcinogenic and toxic material, with acute oral toxicity [54]. Therefore, the selection of resins that could reduce the amount of dangerous, volatile compounds emitted, coupled with producing high-performance particleboards that have a low impact on the environment are among the main goals of this research.

The use of PF and PUF adhesives, which emit lower levels of formaldehyde compared to UF and are less expensive and less toxic than pMDI, is recommended for manufacturing particleboards from agricultural fibers. Unlike pMDI, PF and PUF are not considered highly toxic, making them more suitable for sustainable applications [55]. PF adhesives tend to be more chemically stable and less susceptible to hydrolysis than UF resins and they are fast curing, but provide reduced mechanical properties [56,57]. Furthermore, approximately 95% of the adhesives used in wood-based composite materials are formaldehyde-based, and they can emit formaldehyde at levels up to 0.079 mg/m^2·h exceeding the threshold considered safe for human health [58]. In comparison, traditional PF adhesives typically emit lower levels, around 0.057 mg/m^2·h [59]. Thus, compared to UF and pMDI, PF and PUF adhesives offer lower material costs and reduced environmental impact.

This study used bagasse, kenaf, and hemp fibers with phenol-formaldehyde (PF) and phenol-urea-formaldehyde (PUF) adhesives to produce high-performance particleboards. A simple pH modification treatment was applied to enhance fiber–resin adhesion. The structural chemical changes were and analyzed using Fourier transform infrared (FTIR) spectroscopy. Mechanical properties were compared to panels made from industrial softwood and to those bonded with the high-performance but costly and toxic pMDI adhesive. The study aimed to show the effectiveness of pH treatment in improving resin reactivity using FTIR to demonstrate the differences between the treated and untreated fibers and to assess how fiber morphology impacts panel performance, supporting the development of sustainable alternatives to conventional wood-based boards.

2. Materials and Methods

2.1. Materials

2.1.1. Lignocellulosic Materials

Kenaf was planted at the experimental farm of Khartoum University, Sudan. Kenaf bast fibers (KBF) were water retted and dried at room temperature according to a method reported by Bledzki, A. et al., 2015 [60]. The bagasse was collected from White Nile Sugar Factory at Algenaid in the White Nile State, Sudan. The fibers were air dried and kept in polyethylene bags. Hemp was of type SKF 2, Super kurzfaser, and was purchased from Bafa neu GmbH, Germany.

The softwood was supplied by Rettenmaier & Söhne GmbH + CO KG (Rosenberg, Germany); its color was yellow and the particle size ranged from 300 µm to 500 µm.

NaOH pellets, with a concentration of ≤100%, were purchased from Merck.

2.1.2. Binding Materials

All the adhesive materials were purchased from Dynea Company. Phenol-Urea-Formaldehyde (PUF, commercial code 10J227), PMD, PF (commercial code 4976), was used as a powder and prepared by dissolving 50/50 (*w*/*w*) in water at room temperature.

2.2. Methods

2.2.1. Fiber Grinding

Kenaf and bagasse were initially cut to a size of 5 mm. They were then further ground together with hemp fibers using a Cutting Mill SM 300 (RETSCH GmbH, Haan, Germany) resulting in fiber sizes of approximately 1 mm or less, and used for fiber morphology, Fourier transform infrared (FTIR) spectroscopy analysis, and panel manufacturing.

2.2.2. Fiber Morphology Analysis

Fiber morphology; length, thickness, and aspects ratios were determined according to a method described by Osman, et al., 2025 [61]. Fiber samples were scanned using a flatbed scanner at 1200 dpi and processed with Fibreshape software. Approximately 26,893 fibers per sample were analyzed using a predefined mask ("Example Wood Shred 1200 dpi"). The software measured fibers as ideal rectangles, with a minimum detectable thickness of 40 µm. Percentile analysis was performed to evaluate the distribution and variability of fiber dimensions.

2.2.3. Preparation of the pH-Modified Fiber FTIR Spectroscopy Analysis

To modify the pH of the fibers, an alkaline solution was prepared by dissolving sodium hydroxide (NaOH) in distilled water at a concentration of 33 wt.%. The solution was stirred vigorously to ensure complete dissolution of the NaOH. Subsequently, 2 g of the powdered fiber from each type was placed in a beaker containing a small amount of distilled water. While continuously stirring, the alkaline solution was added dropwise until the pH of the mixture reached either 11 or 13. The treated fibers were then separated by vacuum filtration. Both untreated and treated fibers were dried in an oven at 60 °C for 48 h to eliminate residual moisture.

2.2.4. Fibers' pH Modification for the Panels Production

A regular procedure for modifying the pH was used for the fibers of 1 mm size. NaOH solution 33% concentration was prepared and added slowly to each of the fibers while monitoring the pH until the recommended pH value was achieved. The excess solution was drained off and the fibers were dried at 105 °C overnight, prior to their blending with the different adhesives.

2.2.5. FTIR Spectroscopy Analysis

Fourier transform infrared (FTIR) spectroscopy was conducted using a JASCO FT/IR-4700 spectrometer (JASCO ATR, Tokyo, Japan) equipped with an Attenuated Total Reflectance (ATR) accessory to analyze the functional groups and molecular structures of unmodified and pH-modified bagasse, kenaf, and hemp fibers (treated at pH 11 and 13). Spectra were recorded over the range of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}, averaging 32 scans per measurement to optimize the signal-to-noise ratio and acquisition time. Approximately 0.2 mg of each sample was analyzed without additional preparation [62], ensuring intimate contact with the ATR crystal surface using a built-in pressure clamp applying ~50 N of force. All spectra were processed using the baseline correction and ATR correction functions in the Jasco Spectra Manager software (version: 2.15.02, JASCO, Tokyo, Japan) to minimize baseline slope artifacts and compensate for penetration depth variations. Three replicate scans were performed for each sample to enhance reproducibility. The ATR unit incorporated a durable diamond/ZnSe/germanium crystal, providing reliable performance and broad spectral coverage.

2.2.6. Panel Manufacturing

Duplicate one-layer particleboards (350 × 310 × 16 mm) were produced using various pH-modified and unmodified fibers and adhesives. Adhesive loading levels were 13% for PF and PUF, and 5% for pMDI. Fibers and adhesives were mixed in a laboratory mixer, with adhesives applied manually via spraying. Target board densities ranged from 600 to 680 kg/m^3. Panels were pressed at 180 °C using press plates, under a maximum pressure of 3.5–4.0 N/mm^2, with a pressing time of 30 s per millimeter of thickness. Panel thickness was controlled with 16 mm stoppers and verified manually using a vernier caliper 2.2.4.

Three days prior testing, panels were stored in a conditioning room at 20 °C and 65% relative humidity until reaching equilibrium humidity. They were then trimmed and test specimens were prepared according to BS EN 326:1994 [63].

The mechanical properties, namely, internal bond (IB) strength, modulus of rupture (MOR), and modulus of elasticity (MOE), were investigated in accordance with BS EN 319:1993 and EN 310:1993, respectively [64,65]. Physical properties, such as thickness swelling (TS), were determined based on EN 317:1993 [66]. Samples were immersed in distilled water for 24 h before thickness measurements.

3. Results and Discussion

3.1. Results of Fiber Morphology Analysis

Table 1 [61] shows that kenaf, bagasse, and softwood have similar fiber lengths, around 1 mm, with comparable size distributions, while hemp fibers are shorter and thinner. Kenaf has the highest aspect ratio, indicating the largest surface area. This suggests higher reactivity compared to the other fibers.

Table 1. Results of the fiber shape analysis for the untreated fibers.

Fibers	Length Mean Value [μm]	Thickness Mean Value [μm]	Aspect Ratio
Kenaf	1281.25 ± 17.1 *	104.42 ± 0.8 *	12.27
Bagasse	1175.29 ± 10.5 *	197.36 ± 1.5 *	5.96
Softwood	1638.13 ± 8.4 *	272.43 ± 2.3 *	6.01
Hemp	588.06 ± 3.2 *	103.95 ± 0.28 *	5.66

* Standard deviation.

3.2. Results of Fourier Tranform Infrared (FTIR) Spectroscopy Analysis

The FTIR spectra of kenaf, bagasse, and hemp fibers (Figures 1–3), both untreated and treated with alkaline solutions at pH 11 and 13, reveal notable chemical modifications (Tables 2–4). These changes significantly affect fiber–matrix interactions and, in turn, influence the mechanical performance of the resulting composite panels [67]. Alkaline treatments, particularly with sodium hydroxide (NaOH), are known to remove non-cellulosic components such as hemicellulose, lignin, pectin, and waxes from natural fibers. This process exposes more reactive hydroxyl (–OH) groups on the cellulose surface, enhancing fiber–matrix adhesion through improved hydrogen bonding and surface roughness. The disappearance or reduction of specific FTIR peaks associated with these components serves as evidence of such chemical modifications.

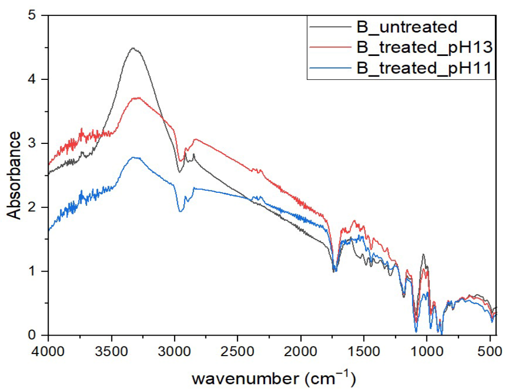

Figure 1. Fourier transform infrared spectroscopy analysis (FTIR) of untreated and treated Bagasse fiber at pH 11 and pH 13.

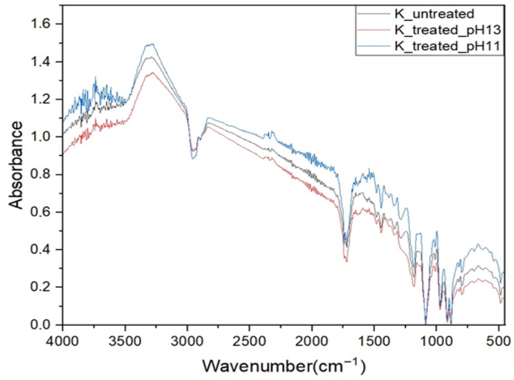

Figure 2. Fourier transform infrared spectroscopy analysis (FTIR) of untreated and treated Kenaf fiber at pH 11 and pH 13.

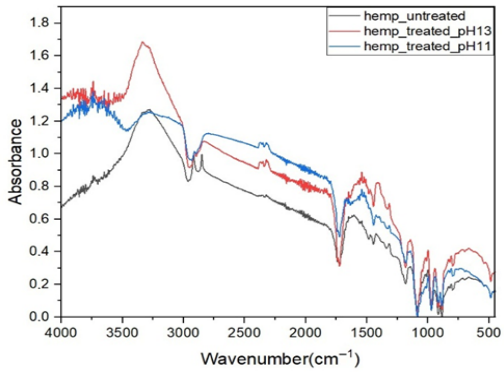

Figure 3. Fourier transform infrared spectroscopy analysis (FTIR) of untreated and treated Hemp fiber at pH 11 and pH 13.

Table 2. Characterization of FTIR spectral analysis of Bagasse fiber.

Bond-Functional Group	Wavenumber, cm^{-1}			Intensities		
	Initial pH	pH 11	pH 13	Initial pH	pH 11	pH 13
O–H Free hydroxyl-stretching	3337.21	3319.85	3315.03	100	61.64	82.19
C–H stretching	2843.52	2914	2848	63.04	52.05	68.50
C=O stretching	1737.55	1728.87	1737.55		Disappeared	
C–O–C and C–O stretching	1254.47	1246	1153.22	27.40	13.70	22.60

Table 3. Characterization of FTIR spectral analysis of Kenaf fiber.

Bond-Functional Group	Wavenumber, cm^{-1}			Intensities		
	Initial pH	pH 11	pH 13	Initial pH	pH 11	pH 13
O–H Free hydroxyl-stretching	3297.67	3315.95	3296.71	95.71	100	90.71
C–H stretching	2830.92	2838.70	2835.81	72.14	73.57	71.43
C=O stretching	1725.97	1725.01	1727.90		Disappeared	
C–O–C and C–O stretching	1244.82	1234.75	1313.25	27.14	32.90	21.43

Table 4. Characterization of FTIR spectral analysis of Hemp fiber.

Bond-Functional Group	Wavenumber, cm^{-1}			Intensities		
	Initial pH	pH 11	pH 13	Initial pH	pH 11	pH 13
O–H Free hydroxyl-stretching	3309.25	3283.21	3304.42	100	73.61	73.61
C–H stretching	2849.31	2914.87	2826.16	59.72	65.97	63.19
C=O stretching	1717.29	1722.12	1726.92		Disappeared	
C–O–C and C–O stretching	1318.14	1315.21	1316.17	30.55	36.11	62.50

3.2.1. Bagasse Fiber

Bagasse fibers exhibited the most pronounced structural transformations following alkaline treatment at pH 11 (Figure 1 and Table 2). The complete disappearance of the carbonyl (C=O) peak (~1737 cm^{-1}) and a significant reduction in the C–O–C/C–O stretching band intensity (27.4 to 13.7%) indicate extensive removal of hemicellulose and waxy components, which typically hinder fiber–adhesive interactions. Though the O–H stretching band intensity dropped significantly (100 to 61.64%), this likely reflects the loss of hemicellulose-bound hydroxyls rather than cellulose-bound ones, suggesting improved surface purity. This observation was in line with what had been reported by Wang, X. et al., 2019 [68] when they treated the jute fibers with hot NaOH and found that the treatment improved the cellulose crystinality and resulted in improved mechanical properties.

It worth noting that the partial recovery of both O–H and C–O–C band intensities observed at pH 13 could be attributed to possible reorientation or degradation of cellulose chains, but without further improvement in chemical reactivity. These structural modifications explain why bagasse panels exhibited the highest mechanical properties at pH 11. The treatment at this condition optimized fiber reactivity without over-degradation, improving adhesion with PF and PUF resins.

3.2.2. Kenaf Fiber

Kenaf fibers also responded positively to alkaline treatment at pH 11. The shift of the O–H stretching peak from 3297 to 3316 cm^{-1} and its increased intensity (from 95.71 to 100%), Table 3, indicates greater exposure of reactive hydroxyl groups, which favor hydrogen bonding and mechanical interlocking with the matrix. Additionally, the disappearance of the C=O band (~1726 cm^{-1}) signifies successful hemicellulose removal. A moderate increase in the C–O–C stretching intensity (27.14 to 32.90%) further supports enhanced exposure of cellulose or lignin ether bonds. However, treatment at pH 13 led to a decline in all key band intensities, pointing to fiber over-treatment, which likely disrupted the cell wall structure making wholes and diminished adhesive interaction [69–71]. These findings correlate with the mechanical results, where kenaf panels performed well at pH 11 but degraded at pH 13.

3.2.3. Hemp Fiber

Unlike bagasse and kenaf, hemp fibers showed limited chemical enhancement through alkaline treatment (Figure 3 and Table 4). Although the C=O band was removed, the intensity of the O–H stretching band dropped significantly (from 100 to 73.61%) and remained unchanged between pH 11 and 13, suggesting only partial exposure of reactive groups. While the C–H stretching region showed moderate increases in intensity, possibly due to surface rearrangement of aliphatic components, this did not translate into improved adhesion [72].

Interestingly, the C–O–C stretching band intensity increased progressively from pH 11 to pH 13 (30.55 to 62.50%), implying continued exposure of lignin/cellulose backbones.

However, this overexposure may reflect deeper structural disruption rather than effective functionalization [73]. The subdued chemical reactivity aligns with hemp's inferior mechanical performance compared to kenaf and bagasse.

3.3. Mechanical Properties

3.3.1. Internal Bond (IB)

Figure 4 presents the internal bond (IB) strength results for panels fabricated from three types of fibers, along with softwood. This test was conducted to evaluate the interfacial bonding strength of the fibers within the composite panels. Among the fibers examined, bagasse and kenaf exhibited the highest mean IB values across all resin types when treated at modified pH levels. The maximum IB value was recorded for bagasse combined with PUF at pH 11 (0.76 N/mm^2), followed by kenaf with PF at pH 13 (0.67 N/mm^2). Notably, all IB values obtained from panels incorporating kenaf and bagasse fibers with both adhesives at the modified pH conditions exceeded the minimum threshold specified by EN 312-6:2010 for heavy-duty load-bearing boards intended for use in dry environments [74].

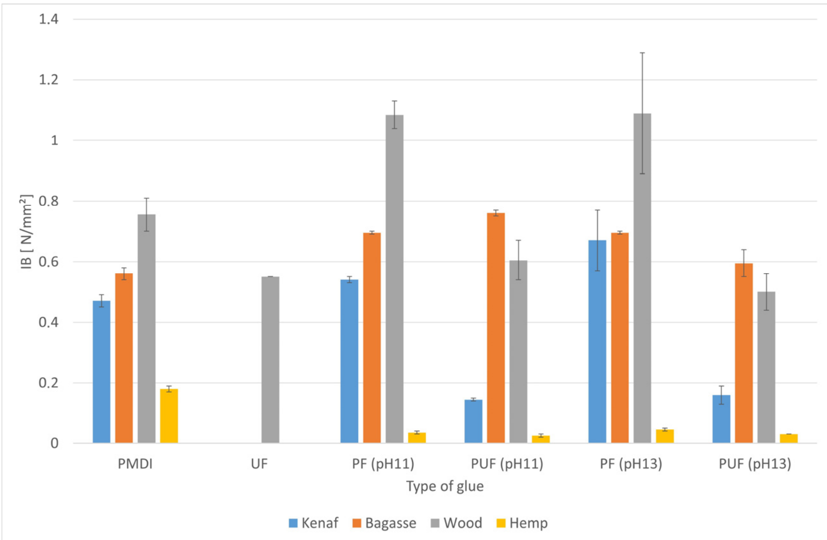

Figure 4. Internal bond for the biocomposites made from the four fibers.

These values were also higher than those obtained using pMDI. The alkaline environment at pH 11 appears to enhance fiber–matrix adhesion by partially removing lignin, hemicelluloses, and waxes, leading to cleaner fiber surfaces and a denser cellulose structure, as shown by FTIR analysis [47]. This treatment increases the nucleophilicity of phenolic rings by exposing reactive hydroxyl groups through lignin and hemicellulose removal. Deprotonation under alkaline conditions raises the electron density on aromatic rings, promoting stronger interactions with the electrophilic sites of PUF and PF adhesives during polymerization, thereby improving interfacial bonding [75]. FTIR spectra confirm this effect with reduced peaks for lignin and hemicellulose (1720 and 1240 cm^{-1}) and increased O–H stretching intensity at 3330 cm^{-1}, indicating a more reactive, hydroxyl-rich surface [47,70,76].

The superior performance of bagasse, surpassing that of kenaf, hemp, and wood when combined with PUF resin, may also be attributed to specific morphological characteristics. Bagasse fibers possess a unique structure that includes a significant proportion of pith fibers, which may contribute to enhanced bonding with the resin matrix. Additionally, bagasse exhibits a lower aspect ratio (5.96) (Table 1) compared to kenaf (12.27), and slightly higher than the value of the hemp (5.66), which may influence fiber dispersion and interfacial adhesion within the composite [61].

It implies that bagasse possessed finer fibers, providing a larger surface area for adhesive bonding, enhancing the adhesive penetration and bonding strength within the panels. Similar trends were observed where molded products made from bagasse pith exhibited higher bending strength compared to those made from depithed bagasse. This can be attributed to the structure of the pith region, which contains large, thin-walled parenchyma cells. These pith particles are more easily deformed and can pack more tightly than rind particles, resulting in an increased self-bonding area [77].

The lower IB values unexpectedly produced by PMDI could be related to the fact that pMDI resin can be more difficult to use in production since its sticky nature easily creates build-up on the surfaces of the press.

The IB of Kenaf-based panels varied significantly with the type of adhesive and fiber treatment, with the highest IB achieved for panels bonded with PF adhesive at pH 13. It was observed that the obtained values were higher than those reported in the literature, particularly those achieved using heat-treated bagasse fibers [78], with the addition of 30% eucalyptus particles [28], and with fibers treated with citric acid [79]. Furthermore, the values achieved using bagasse and kenaf exceeded those obtained from agricultural fibers combined with UF resin, which have generally been found suitable only for furniture applications [80].

It has been observed that the treatment at pH 11 also yielded notable improvements in IB, particularly with both PF and PUF adhesives, compared to the untreated and UF-bonded panels. FTIR analysis supports these findings by revealing key structural modifications induced by alkaline treatment. At pH 11, the intensity of the O–H stretching band increased (from 95.71 to 100%), indicating a more hydroxyl-rich surface due to the partial removal of lignin and hemicelluloses and enhanced interfacial bonding with the adhesives. Additionally, the disappearance of the C=O stretching peak and the increased C–O stretching intensity at pH 11 (from 27.14 to 32.90%) further confirm the removal of amorphous components and the exposure of cellulose functionalities. In contrast, treatment at pH 13 resulted in a decrease in O–H and C–O intensities, suggesting potential over-degradation of the fiber surface, which may explain the reduced bonding performance with PUF under these conditions.

In contrast, the internal bond strength of hemp-based panels remained low across all treatments and could not meet the standard value. It reflects limited improvement in fiber–adhesive interactions. This observation was supported by FTIR analysis which shows a significant reduction in O–H stretching intensity after alkaline treatment at both pH 11 and pH 13 (from 100 to 73.61%), indicating decreased availability of reactive hydroxyl groups. Although the intensity of C–O–C and C–O stretching bands increased—especially at pH 13 (from 30.55 to 62.50%)—this did not correspond to improved bonding. The disappearance of the C=O peak suggests the removal of lignin or hemicellulose, but the overall chemical and structural modifications were insufficient to enhance interfacial adhesion. These results indicate that alkaline treatment alone may not be effective in improving the bonding performance of hemp fibers in particleboard applications.

Furthermore, this low performance may be due to the larger volume of hemp fibers compared to the others, which led to insufficient contact between particles and, consequently, poor adhesion quality [81].

It is worth noting that the differences observed among the three fibers underscore how fiber type and surface chemistry respond differently to alkaline treatment and adhesive systems, primarily due to their distinct biochemical compositions and morphological characteristics. While alkaline treatment enhanced bonding by exposing reactive sites for bagasse at pH 11 with PUF, the best performance of kenaf was obtained with PF adhesive at pH 13. The hemp appears to exhibit a more chemically resistant surface or a denser structure that responds poorly to such treatment.

Notably, the values obtained using bagasse with PUF exceeded those achieved with softwood using the same adhesive. In addition, the IB values for both bagasse and kenaf with PF surpassed the EN 312-6:1996 standard requirements [82]. This finding is significant from both economic and environmental perspectives, as it suggests that these fibers could effectively replace softwood particles while utilizing more affordable adhesives like PUF. Moreover, the use of pMDI is restricted in some countries due to health and safety concerns for workers, further highlighting the potential advantages of alternative adhesives.

3.3.2. Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

Figures 5 and 6 show, respectively, the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) results of the three fibers used to fabricate particleboards with different adhesives, including softwood. It was observed that the highest mean MOR and MOE values were produced by the kenaf particleboard bonded with PUF at pH 11.

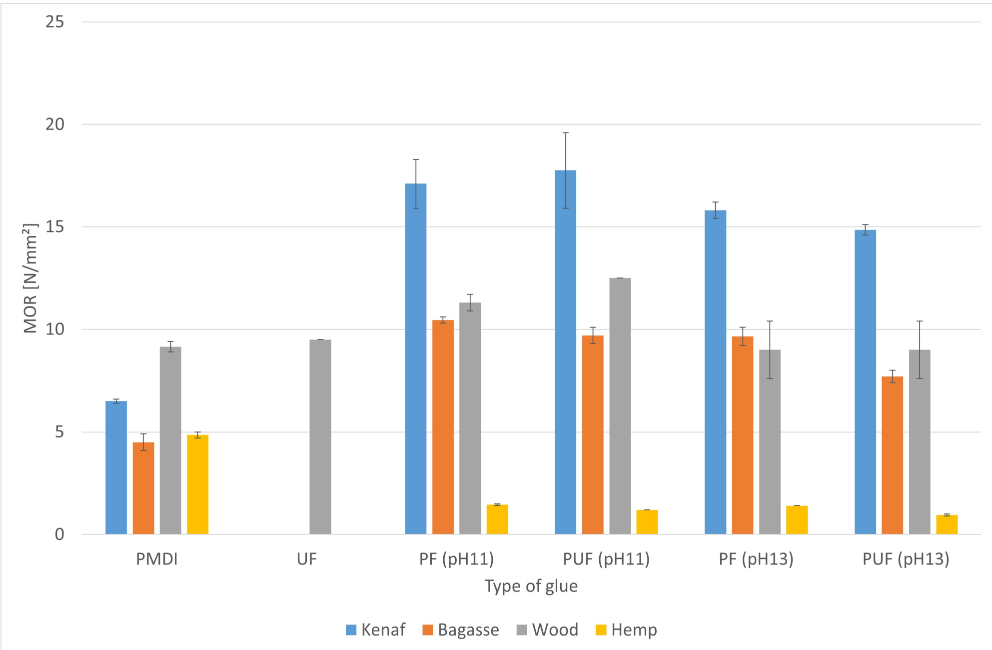

Figure 5. MOR for the biocomposites made from the four fibers.

These results demonstrate that pH modification had a significant influence on bending strength, with both MOR and MOE values exceeding the standard requirements (15 N/mm^2) specified in EN 312-4:2010 for load-bearing boards intended for dry conditions [74]. Moreover, these values were higher than those achieved with softwood fibers. However, further increasing the pH beyond 11 did not lead to significant improvements, as the values obtained at pH 13 with both PF and PUF showed a slight decline. This observation is environmentally and economically significant because achieving optimal adhesive curing at pH 11 reduces the need for stronger alkaline conditions, which often require additional chemicals, energy, and safety measures. Maintaining pH 11 simplifies processing, lowers operational costs, and minimizes equipment corrosion. It also reduces adhesive waste and ensures consistent bonding efficiency, making large-scale production more cost-effective.

A similar trend was observed in particleboards made from bagasse, although the MOR and MOE values were lower than those of kenaf, despite comparable panel densities. For hemp fibers, no improvement in MOR and MOE values was observed. The best values were obtained using PMDI, although still below the EN standard. Interestingly, both PF and PUF resulted in higher values than PMDI, potentially due to the low resin loading (5%) relative to the low bulk density of hemp. This imbalance may have resulted in insufficient resin coverage on the fiber surfaces [83,84].

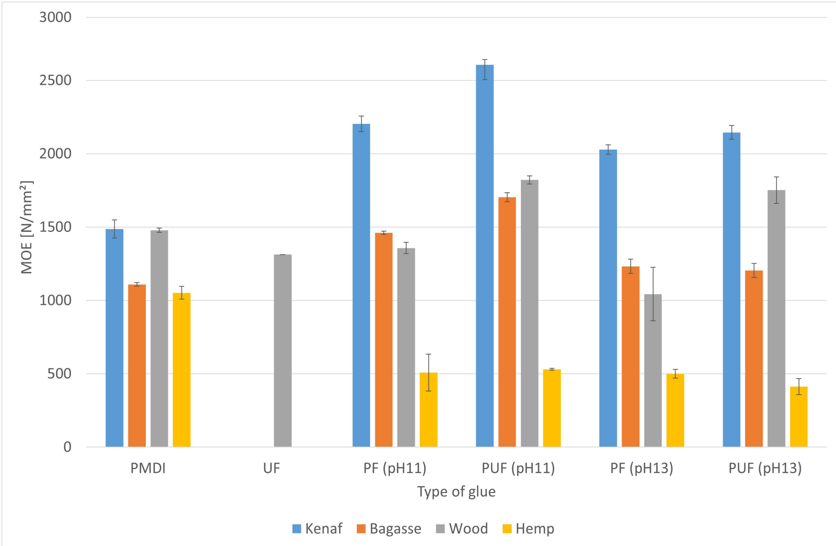

Figure 6. MOE for the biocomposites made from the four fibers.

In contrast, hemp performed poorly with all adhesives used in this study at all pH values, being less responsive to the alkaline treatment. This could also be due to its high content of fine particles, which led to uneven resin distribution during panel fabrication [85,86]. Consequently, the adhesion was inadequate, leading to low-density panels with suboptimal mechanical properties. Notably, particleboards made from hemp exhibited the lowest density (Table 5), while those made from kenaf showed the highest. Furthermore, the substantially lower bulk density of hemp fibers compared to wood introduces challenges in forming a uniform pressing mat. This often necessitates reducing the target board density, which can further compromise the mechanical properties of the final product [87].

Table 5. Average densities of the fiber-based particleboard.

Fibers	Mean Density (kg/m^3) Values	Standard Deviation (SD)
Kenaf	671.20	5.9
Bagasse	662.40	5.4
Hemp	604.70	5.3
Wood	691.40	5.5

Importantly, the mechanical results are in strong agreement with the FTIR analysis. Bagasse at pH 11 showed the highest mechanical performance, corresponding to FTIR evidence of effective removal of hemicellulose and partial delignification, resulting in the exposure of more accessible hydroxyl groups and increased nucleophilic reactivity [88,89]. This chemical activation enhances bonding with polar adhesives like PUF and PF. Kenaf followed a similar trend, though with slightly lower FTIR peak intensity changes, aligning with its slightly reduced mechanical properties. Conversely, hemp did not exhibit significant changes in hydroxyl group exposure based on the FTIR results, explaining its poor fiber–resin interaction and consequently lower mechanical performance [90,91].

To conclude, based on mechanical performance, kenaf and bagasse with modified pH treatment can be considered promising alternative biomass sources for the production of high-performance particleboards. These fibers demonstrated the potential to effectively replace conventional wood fibers in various applications.

3.4. Physical Properties

Thickness Swelling for 2 h and 24 h

The thickness swelling test, though not required for the type of boards targeted in this study, was performed to assess the effect of pH modification on the physical properties of the produced boards. The results of thickness swelling for 2 h and 24 h are presented in Figures 7 and 8.

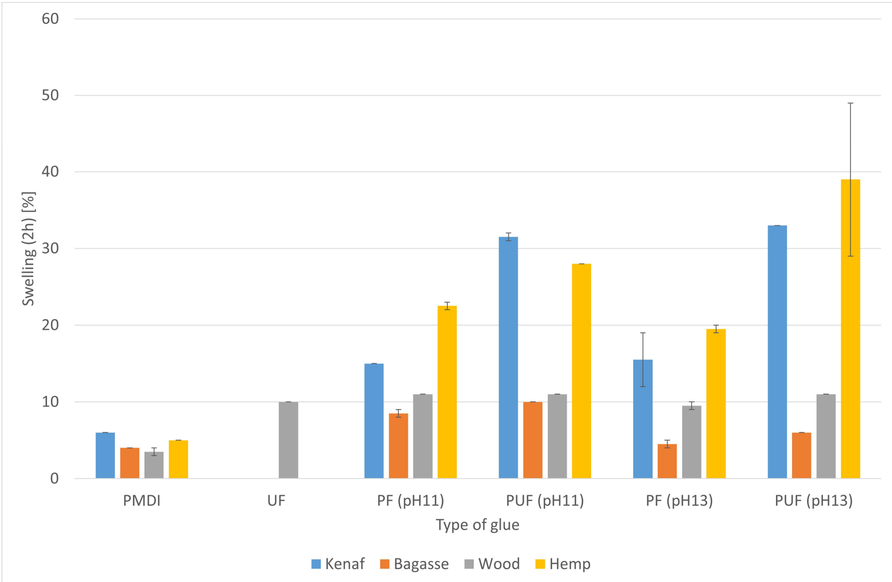

Figure 7. TS 2 h for the biocomposites made from the four fibers.

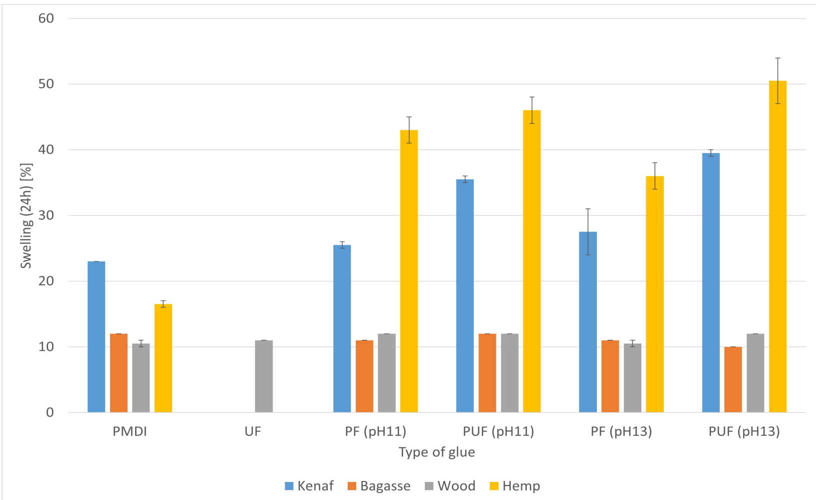

Figure 8. TS 24 h for the biocomposites made from the four fibers.

Bagasse-based particleboards demonstrated consistently low thickness swelling values across all adhesives, remaining below 11% after 2 h of water immersion (Figure 7). The lowest swelling was observed with PMDI adhesive (~3.5%). These values are not only well below the maximum limits set by the EN 312-4 standard [74], but are also lower than those reported in previous studies, where reduced swelling was attributed to the use of elevated pressing temperatures (e.g., 260 °C) [92]. The results of this study are particularly significant given that one of the commonly cited drawbacks of using bagasse in particleboard production is its poor dimensional stability due to its high-water absorption tendency. Remarkably, the swelling behavior after 24 h (Figure 8) also confirmed the excellent water resistance of bagasse panels, which maintained similar low swelling levels as observed after 2 h.

The alteration of the pH of the bagasse was found to improve their physical properties. This could be interpreted using the FTIR analysis of bagasse fibers treated at pH 11, which reveals a marked reduction in the intensity of the carbonyl (C=O) stretching vibration around 1737 cm^{-1}, indicating substantial removal of hemicellulose components. Additionally, the decrease in the C–O–C stretching band intensity suggests the elimination of waxy substances and lignin, leading to a cleaner fiber surface. These chemical changes enhance the hydrophobicity of the fibers, resulting in lower water uptake and improved dimensional stability, as evidenced by reduced-thickness swelling values in particleboards fabricated from these treated fibers. This observation aligns with findings from previous studies, where alkali-treated bagasse fibers exhibited improved physical properties in composite material due to a change in the chemical composition [93,94].

Furthermore, the improved thickness swelling could also be attributed to the presence of short fibers, as reflected by its low aspect ratio, which is comparable to wood and lower than that of Kenaf and Hemp fibers. Additionally, the presence of parenchyma cells (pith), which were reported to have high compaction ratios, resulted in denser and more dimensionally stable boards [95,96].

Kenaf also showed FTIR signs of effective treatment at pH 11, including a shift of the O–H band to higher wavenumbers (3297→3316 cm^{-1}) and increased intensity (95.71→100%), reflecting exposure of reactive hydroxyls that support bonding. However, over-treatment at pH 13 led to the reappearance or weakening of bands, suggesting fiber degradation and less effective adhesive interactions. This chemical modification paralleled the increased swelling and weakened physical properties seen in kenaf panels at higher pH. Moreover, kenaf fibers, characterized by a high aspect ratio [61], suggest the presence of thinner, elongated fibers. Combined with their low bulk density (0.10–0.20 g/cm^3) [21], they tend to occupy a larger volume relative to the adhesive content. This may lead to the formation of more porous panels that are more susceptible to water uptake and dimensional instability. Supporting this, several studies have shown that kenaf undergoes swelling and micro-cracking when exposed to moisture, increasing water absorption and weakening the fiber–matrix interface [97].

Hemp-based panels displayed varied physical properties. This variation may be linked to the inherently high hygroscopicity of hemp fibers, which is well-documented in the literature [98] and is potentially associated with their low lignin content; a key factor in hydrophobicity and water resistance [99].

The hemp panels showed relatively high thickness swelling at both 2 h and 24 h, particularly when bonded with PMDI. This could be related to the fact that hemp fibers showed less favorable chemical modification under alkaline treatment. Although the C=O band was eliminated, the O–H intensity decreased (from 100 to 73.61%) and plateaued, indicating limited reactive group exposure. Despite a progressive increase in C–O–C intensity (30.55 → 62.50%), this did not correlate with better adhesion, suggesting overexposure and possible structural deterioration. Consequently, FTIR data support the observed inferior dimensional stability and swelling behavior of hemp-based boards. Additionally, this may also be due to uneven adhesive coverage stemming from their low bulk density and the fine nature of the particles.

In addition to fiber alkaline treatment and fiber morphology, board density (Table 5) significantly influenced the physical performance of the panels. While bagasse panels exhibited lower density than kenaf panels, they performed better in terms of thickness swelling. This apparent anomaly could be attributed to the more compact and wood-like morphology of bagasse fibers, which results in enhanced internal bonding and lower void content characteristics that are crucial for minimizing moisture ingress.

In conclusion, while density is important, the combination of FTIR data and physical test results underscores the critical role of fiber surface chemistry and morphology. Bagasse, with optimal pH treatment, displayed the best integration of favorable chemical changes and dimensional stability. Kenaf responded well to mild alkali treatment but was sensitive to over-treatment. Hemp, by contrast, showed limited functionalization and suffered from inferior performance. Thus, understanding and optimizing chemical treatment conditions based on fiber-specific behavior is essential for developing moisture-resistant, high-performance particleboards from agricultural residues.

4. Conclusions

This study highlights the potential of kenaf and bagasse fibers as viable alternatives to industrial softwood for the production of high-performance biocomposites. The morphological analysis shows that kenaf, bagasse, and softwood fibers share similar lengths, around 1 mm, while hemp fibers are shorter and thinner, with kenaf exhibiting the highest aspect ratio and thus greater potential chemical reactivity. Alkaline treatment at pH 11 effectively removes non-cellulosic components such as hemicellulose, lignin, pectin, and waxes, exposing reactive hydroxyl groups that enhance fiber–matrix adhesion.

Bagasse fibers showed the most significant chemical changes after treatment at pH 11, with the disappearance of the carbonyl peak (~1737 cm^{-1}) and a marked reduction in C–O–C stretching intensity, indicating extensive removal of hemicellulose and waxes. Although O–H stretching intensity decreased, this was attributed to loss of hemicellulose-bound hydroxyls rather than cellulose hydroxyls, suggesting enhanced surface purity. These chemical changes correlated with superior mechanical performance due to optimal fiber reactivity without over-degradation.

Kenaf also benefited from pH 11 treatment, with shifts in O–H stretching peaks and increased intensity indicating greater exposure of reactive groups, alongside the removal of hemicellulose, as evidenced by the disappearance of C=O bands, but higher alkalinity at pH 13 led to structural damage and reduced bonding quality.

Hemp fibers showed limited chemical enhancement; although hemicellulose removal was evident, the O–H band intensity decreased and remained unchanged between pH 11 and 13, indicating only partial exposure of reactive groups. An increase in C–O–C band intensity at higher pH likely reflected deeper structural damage rather than improved functionality, corresponding with poorer mechanical properties.

When the pH-modified fibers were bonded with PF and PUF adhesives, they demonstrated superior mechanical and physical properties compared to the untreated fibers. Bagasse achieved the highest IB of 0.76 MPa with PUF at pH 11, followed closely by 0.70 MPa with PF at the same pH—both exceeding the EN 312-6:2010 standard for heavy-duty load-bearing panels in dry conditions. The highest modulus of rupture (MOR) values was recorded with kenaf at pH 11 for both adhesives, surpassing the EN 312-4:2010 requirements for load-bearing boards, with bagasse also performing comparably to industrial softwood. The highest MOE was reported for kenaf bonded with PUF at pH 11, followed by bagasse under similar conditions. Both kenaf and bagasse outperformed softwood in terms of MOR and MOE when used with PF and PUF adhesives.

Physical properties also favored bagasse and kenaf boards treated at pH 11, exhibiting lower thickness swelling and greater dimensional stability linked to hemicellulose and wax removal. Bagasse consistently exhibited the lowest TS values for 2h and 24h across all pH levels and adhesive types, with TS values falling below those specified in EN 312-4:2010 and comparable to those of softwood-based panels. Hemp boards had the highest swelling and lowest density, reflecting poor fiber–adhesive interaction and mat formation difficulties.

The study demonstrated that the differences observed among the three fibers draw attention to how fiber type and surface chemistry respond differently to alkaline treatment and adhesive systems, primarily due to their distinct biochemical compositions and morphological characteristics.

Overall, this study concludes that the use of pH-modified kenaf and bagasse fibers combined with PF or PUF adhesives offers a promising approach for producing medium-density homogeneous particleboards, replacing wood fibers in particleboard production. The simplicity and cost-effectiveness of the fiber treatment process, alongside the strong performance of the resulting panels, emphasize their potential for commercial application in the construction industry and offer safer and more cost-effective alternatives to the more expensive and toxic pMDI, without compromising panel performance.

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