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Development and Mechanical Evaluation of Banana Stem–Wood Dust Particleboard Using a Phenol-Formaldehyde Binder

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Abstract

The growing demand for sustainable materials has increased interest in converting agricultural and wood-processing residues into value-added composites. In this study, hybrid particleboards were fabricated from banana pseudostem (BPS) and wood dust (WD) using phenol-formaldehyde (PF) resin as binder. Three formulations, namely 100 : 0, 70 : 30, and 50 : 50 (BPS : WD), were prepared under fixed fabrication conditions, including a four-stage hot-pressing cycle at 181 °C. Mechanical testing and scanning electron microscopy (SEM) were used as the main evaluation methods, while Fourier transform infrared spectroscopy (FTIR) was applied as a supportive technique for functional-group identification. Among the tested formulations, the 50 : 50 panel showed the most favourable overall mechanical trend, with the highest tensile, flexural, shear, and compressive values, supported by SEM observations of a denser and more cohesive microstructure. In contrast, the 100 : 0 panel showed weaker bonding and a more porous morphology. FTIR spectra confirmed the presence of characteristic lignocellulosic and resin-related functional groups, but were used only as supportive evidence rather than as a direct basis for ranking performance. Overall, the findings suggest that hybridisation of BPS and WD can improve panel quality under the selected fabrication conditions. However, since the present work represents a preliminary assessment with a limited number of replicates, the reported trends should be interpreted with caution and confirmed in future studies.

Keywords

Banana pseudostem, wood dust, phenol-formaldehyde, hybrid particleboard, mechanical properties, SEM, FTIR

1 Introduction

The increasing demand for sustainable materials has encouraged the use of agricultural and wood-processing residues in composite development. Banana pseudostem (BPS) and wood dust (WD) are two lignocellulosic wastes that are widely available in tropical regions and have potential as alternative raw materials for engineered composite panels. BPS is rich in cellulose, hemicellulose, and lignin, while WD is a fine by-product from sawmills and furniture industries. The combination of these residues offers an opportunity to develop low-density composite materials from renewable waste-based resources.[1–3]

Phenol-formaldehyde (PF) resin remains one of the most established thermosetting adhesives for wood-based composites because of its good bonding performance, thermal stability, and moisture resistance. PF-bonded systems are widely used in applications requiring dimensional stability and durability.[4,5] However, the performance of composite panels is influenced not only by the binder system, but also by particle composition, resin distribution, fibre packing, and fabrication conditions.[3–5]

Although BPS has attracted attention as a potential reinforcement material, its use as a single raw material may be limited by its irregular fibrous morphology and moisture sensitivity.[1] WD may help improve particle packing and density uniformity when used as a hybrid component. Therefore, combining BPS and WD in different ratios may provide a more balanced composite structure with improved mechanical behaviour.[1,3]

The present study aimed to fabricate BPS–WD composite panels bonded with PF resin under controlled pressing conditions, and to evaluate the effect of composition ratio on their mechanical and morphological behaviour. The specific objectives were: (1) to prepare hybrid particleboards with different BPS:WD ratios; (2) to fabricate the panels under fixed hot-pressing conditions; and (3) to evaluate their performance through mechanical testing, SEM, and supportive FTIR analysis.

2 Materials and method

2.1 Raw material preparation

Banana pseudostem (BPS) used in this study was collected from local plantation areas in Perak, Malaysia. Mature stems were cut manually into sections approximately one meter long to facilitate handling and transportation. Each section was then longitudinally split to obtain the central fibrous region, followed by initial sun-drying in an open area near the laboratory until semi-dry, as shown in Fig. 1. Subsequently, they were transferred to the workshop of the

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Forest Research Institute Malaysia (FRIM) for further drying under controlled temperature conditions (approximately 60–70 °C) until a constant weight was achieved.



Fig. 1 – Preparation of banana pseudostem: (a) manual splitting to obtain the fibrous core region; (b) sun-drying of sliced banana stems prior to controlled oven-drying

After complete drying, the BPS was ground into fine particles and sieved to obtain a more uniform particle fraction within the range of approximately 0.1–5.0 mm prior to blending. The resulting powder was stored in airtight containers to prevent moisture absorption. The dried BPS particles and WD were subsequently blended using standard laboratory mixing equipment under controlled preparation conditions at the Forest Research Institute Malaysia (FRIM), Kepong, following routine laboratory practice for material preparation to improve particle homogeneity prior to resin formulation.

2.2 Fabrication process

The fabrication of the composite panels in this study consisted of two main phases: (i) formulation of resin and particles, and (ii) panel forming and curing. This distinction separates the material-preparation stage from the board-fabrication stage. In the present study, a commercial PF resin of resol type was used directly, and the curing reaction took place during hot pressing.

Phenol-formaldehyde (PF) resin is a thermosetting adhesive that forms a cross-linked network during curing.[4,5] The curing process involves methylolation, condensation, and network formation, resulting in methylene bridge formation and a stable thermoset structure.[4,5]

In this study, the PF resin had a solid content of 0.43, and the amount of resin added to the particle mixture was fixed at 5 wt% on a dry-weight basis. The actual curing process occurred during hot pressing at 181 °C under a four-stage pressing cycle.

Fig. 2 schematically presents the main workflow used for particle blending, mat forming, and panel curing in the present study.

2.3 Panel forming and curing process

This phase involved the combination of raw material preparation and board forming under controlled temperature conditions. Fig. 3 presents the overall sequence of panel fabrication and specimen preparation.

BPS and WD particles were dried, sieved, and blended according to the selected weight ratios before being mixed with PF resin. The target density of each panel was set at 0.5 g cm^{-3}, and the calculated mass for a single board of 340 mm × 340 mm × 25 mm was 1445 g. Based on a resin solid content of 0.43 and a fixed resin loading of 5 wt% on a dry basis, the required resin mass was calculated to be 168 g, as demonstrated in Fig. 4. The PF resin was then mixed with the prepared particles to obtain as uniform a coating as possible before pressing.

Based on the established formulation and calculations, the fabrication process proceeded through cold pressing

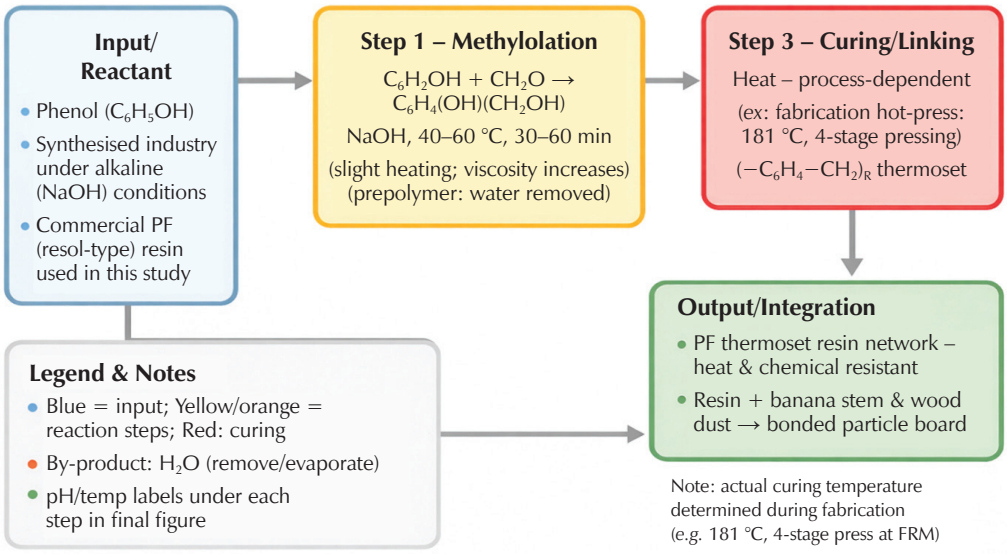


Fig. 2 – Fabrication process workflow

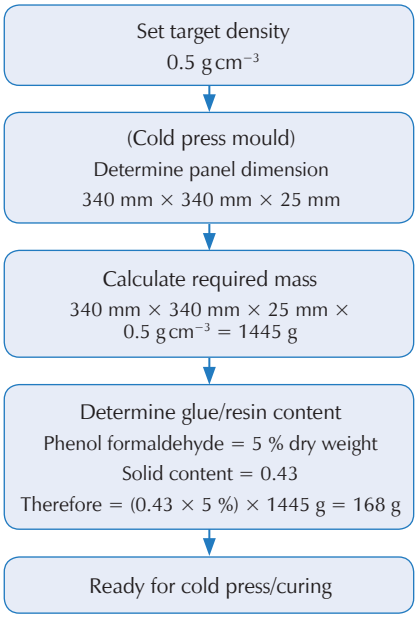


Fig. 3 – Formulation and panel fabrication process



Weight for each mix =
- Sample 1, 100 % dried banana stem fibre = 1445 g
- Sample 2, 70 % dried banana stem fibre = 1011.5 g
  30 % saw dust = 433.5 g
- Sample 3, 50 % dried banana stem fibre = 722.5 g
  50 % saw dust = 722.5 g

Fig. 4 – Calculation and weighing of materials based on the target density and resin ratio prior to mixing

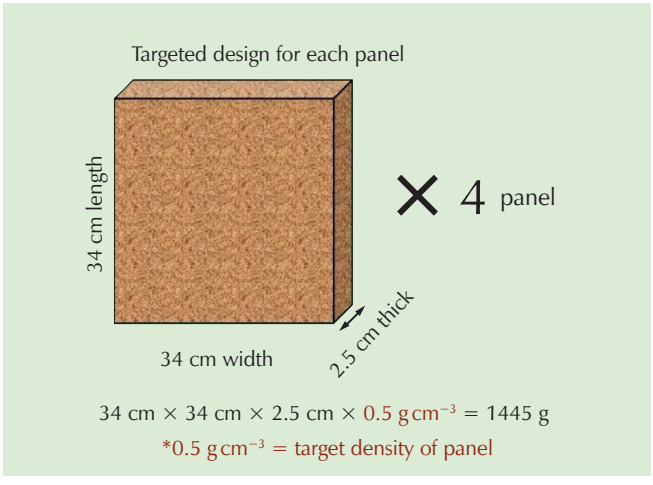
and hot pressing to produce the final composite panels. The homogeneous mixture was first cold-pressed to form a preliminary mat and to stabilise its dimensions. The pre-pressed mat was then subjected to hot pressing at 181 °C using a four-stage pressing sequence. This process allowed resin flow, moisture removal, and resin curing to take place, resulting in consolidation of the composite panel.

After hot pressing, the fabricated composite panels were cooled to room temperature and trimmed to the target dimensions. Each formulation produced a total of four panels corresponding to the designated mix ratios of 100 : 0, 70 : 30, and 50 : 50 (BPS:WD). The fabricated composite panels are shown in Fig. 5(a), while the cutting and trimming process of test specimens is illustrated in Fig. 5(b). The fabricated boards were then cut and trimmed according to the required specimen dimensions for subsequent mechanical testing. The specimen configurations for tensile, flexural, shear, and compression testing are summarised in Table 1.

Table 1 – Specimen configuration for mechanical testing according to ASTM standards

Test Type	Standard	Specimen Configuration
Tensile	ASTM D3039	Prepared according to standard tensile specimen geometry
Flexural	ASTM D790	Prepared according to three-point bending specimen geometry
Shear	ASTM D2718	Prepared according to shear specimen geometry
Compression	ASTM D695	Prepared according to compression specimen geometry

a)



b) Cutting the panel according to decided size

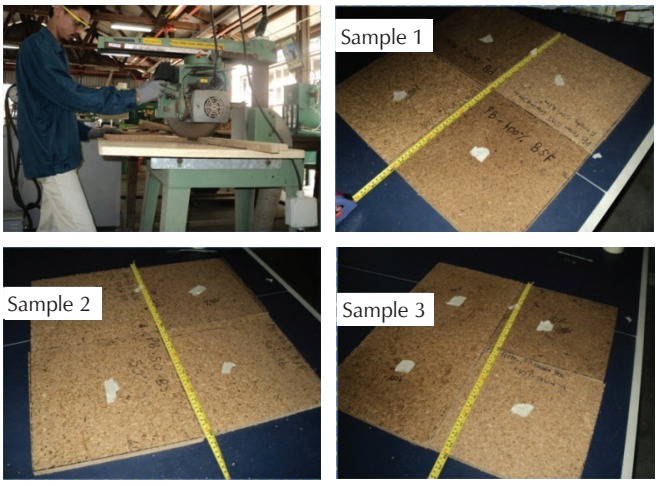


Fig. 5 – a) Fabricated composite panels, and b) cutting and trimming process of test specimens

Table 2 – Summary of testing parameters

Test Type	Standard	Crosshead speed / mm min^{-1}	Replicates / n	Remarks
Three-point bending	ASTM D790	5	2	Flexural strength & modulus
Tensile	ASTM D3039	5	2	Tensile strength & stiffness
Shear	ASTM D2718	5	2	Interfacial bonding strength
Compression	ASTM D695	5	3	Compressive strength & stiffness

The panels were stored in a controlled environment to minimise moisture absorption before mechanical testing and subsequent SEM and FTIR analyses.

2.4 Mechanical testing

Mechanical testing was conducted to evaluate the load-bearing behaviour of the fabricated BPS–WD composite panels. All tests were carried out using a Universal Testing Machine (UTM) (Instron 3365, 5 kN) under standard laboratory conditions with a crosshead speed of 5 mm min^{-1}. The investigated properties included tensile, flexural, shear, and compression behaviour. The corresponding ASTM methods and replicate numbers are summarised in Table 2. Because the present work was intended as an initial feasibility study, the number of replicates was limited for several test modes. Therefore, the mechanical results are presented as descriptive mean values, with standard deviation reported where available, and the observed trends should be interpreted as preliminary.

2.5 Scanning electron microscopy (SEM)

The surface morphology of the composite panels was analysed using a JEOL JSM-6380LA scanning electron microscope operating at 15 kV. Small rectangular specimens (approximately 10 mm × 10 mm) were cut from the fabricated panels and mounted on aluminium stubs using conductive carbon tape. Prior to imaging, the surfaces were coated with a thin layer of gold (Au) *via* sputter coating to enhance electrical conductivity and image resolution. The SEM micrographs, captured at magnifications of ×100, ×500, and ×1000, were used to observe the particle bonding quality, resin dispersion, and interfacial adhesion between banana stem and wood dust fibres.[7]

2.6 Fourier transform infrared spectroscopy (FTIR)

FTIR was used as a supportive method to identify the main functional groups present in the fabricated composite panels.[6,8] The spectra were interpreted with emphasis on bands associated with hydroxyl, aliphatic C−H, aromatic, and C−O related groups from the lignocellulosic constituents and PF resin.[6,8] In the present study, FTIR was used only as supportive chemical information and not as the main basis for explaining differences in mechanical performance.

3 Results and discussion

3.1 Tensile behaviour

Fig. 6 compares the mean force–stroke curves of the three formulations. Among the tested panels, the 50 : 50 formulation recorded the highest mean maximum load (347.03 N), followed by the 70 : 30 panel (221.83 N) and the 100 : 0 panel (118.52 N). The overall trend suggests that the hybridisation of BPS with WD contributed to improved tensile response under the selected processing conditions. However, because of the limited number of replicates and the relatively high variability observed for some samples, these results should be interpreted as preliminary descriptive trends rather than statistically conclusive differences.

Table 3 – Mean tensile properties

Sample	Mean max force / N	Stroke / mm	SD / N
100 : 0	118.52	0.843	0.99
70 : 30	221.83	0.709	75.06
50 : 50	347.03	1.407	222.81

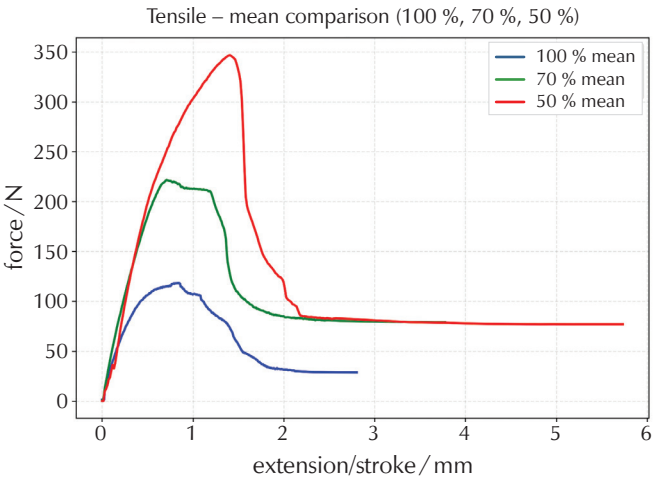


Fig. 6 – Mean tensile force–stroke behaviour of the composite panels

3.2 Flexural behaviour

The flexural results also showed a clear trend of improved performance with hybridisation. The 50 : 50 panel achieved the highest flexural strength (3.02 MPa), while the 70 : 30 panel showed intermediate behaviour, and the 100 : 0 panel showed the lowest flexural performance. This trend suggests that improved particle distribution and matrix continuity may have contributed to better bending resistance in the hybrid panels.

Table 4 – Mean flexural properties

Sample	Max force / N	Stroke / mm	SD / N	Strength / MPa
100 : 0	23.985	4.4891	21.6017	0.3123
70 : 30	164.435	4.3049	16.2816	2.1411
50 : 50	231.624	2.8205	174.6246	3.0159

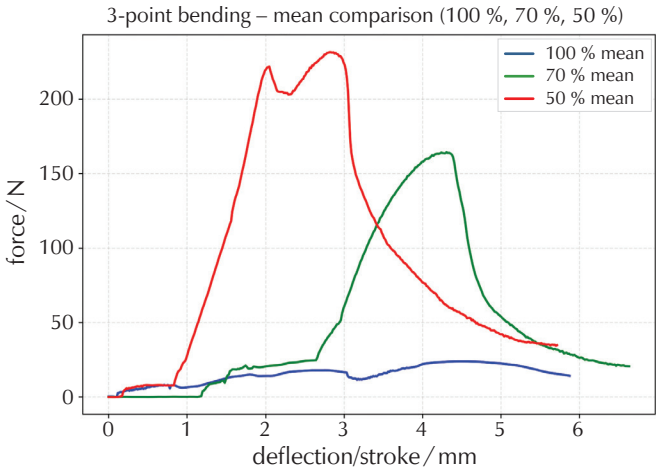


Fig. 7 – Mean flexural force–stroke behaviour of the composite panels

3.3 Shear behaviour

Fig. 8 compares the mean force–stroke curves of the three formulations under shear loading, while the corresponding numerical values are presented in Table 5. The 50 : 50 panel exhibited the highest mean maximum load (1985.63 N), followed by the 70 : 30 panel (764.16 N), and the 100 : 0 panel (219.45 N). The overall trend suggests improved internal cohesion in the hybrid panels under shear loading.

Although the data indicate that the 50 : 50 formulation had the highest shear resistance, the interpretation remains descriptive because of the limited replicate number. The sharper load drop observed after the peak for the 50 : 50 panel may indicate a more brittle failure behaviour compared with the more gradual response of the 100 : 0 panel.

Overall, the shear results suggest that the incorporation of WD may have improved stress transfer and structural compactness under the selected fabrication conditions.

Table 5 – Mean shear properties

Sample	Mean max force / N	Stroke / mm	SD / N
100 : 0	219.45	7.57	17.07
70 : 30	764.16	6.71	24.99
50 : 50	1985.63	6.56	128.10

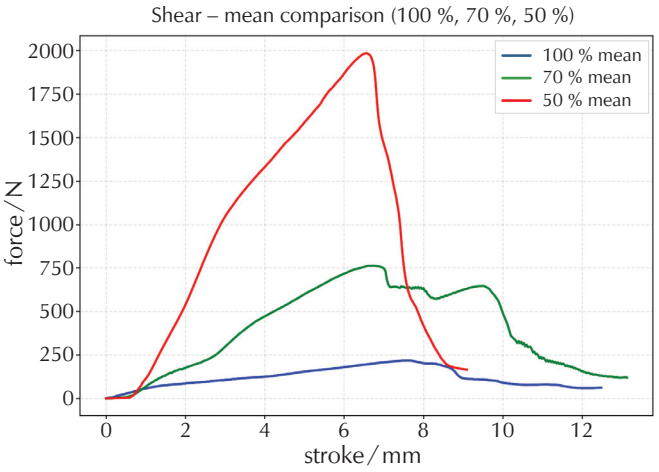


Fig. 8 – Mean shear force–stroke behaviour of the composite panels

3.4 Compression behaviour

Compression test results (Table 6), supported by the stress–strain curves in Fig. 9, indicate a clear trend of increasing compressive capacity from the 100 : 0 formulation to the 50 : 50 formulation. The 50 : 50 panel showed the highest compressive load, which is consistent with the denser structure observed in the SEM images. In contrast, the 100 : 0 panel showed the weakest compression response, which may be associated with its more porous internal structure.

Table 6 – Mean compression properties

Sample	Max force / N	Stroke / mm
100 : 0	989.83	8.765
70 : 30	2831.10	8.562
50 : 50	6972.10	8.469

3.5 SEM morphological analysis

SEM analysis was used to examine the morphology of the composite panels and to relate their structural features to the mechanical results. Representative micrographs of the three formulations showed clear differences in fibre packing, void content, and resin distribution.

The 100 : 0 BPS panel exhibited a relatively porous structure with loosely packed particles and visible voids. Limited

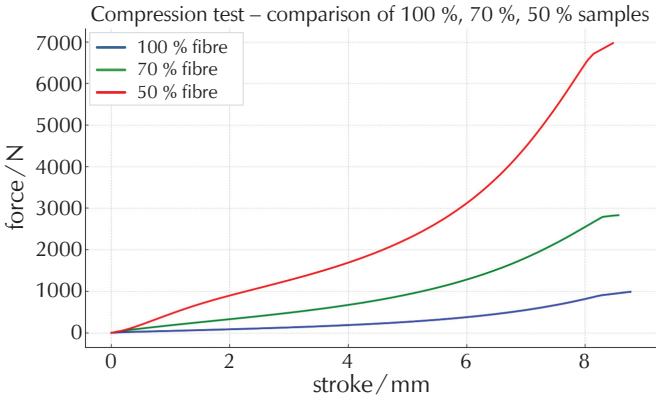


Fig. 9 – Mean compression stress–strain behaviour of the composite panels

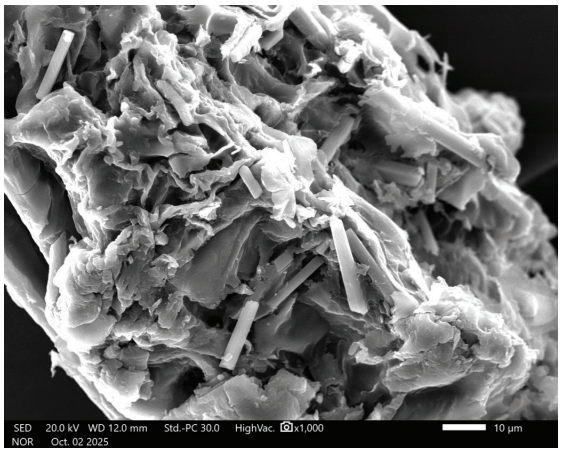


Fig. 10 – SEM micrograph of 100 : 0 BPS-WD composite panel at ×1000 magnification showing porous fibre arrangement and weak resin–fibre interface



Fig. 11 – SEM micrograph of 70 : 30 BPS-WD dust hybrid panel at ×1000 magnification showing improved fibre packing and partial resin coverage

continuity at the interfacial regions suggests less effective stress transfer, which is consistent with its comparatively low mechanical performance.

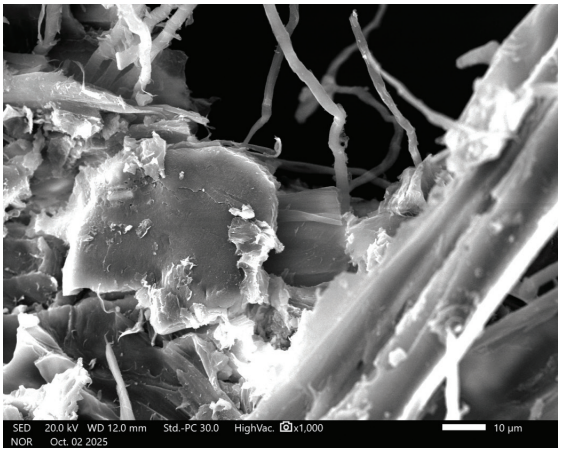


Fig. 12 – SEM micrograph of 50 : 50 BPS–WD hybrid panel at ×1000 magnification showing compact structure and strong resin–fibre adhesion

The 70 : 30 BPS : WD panel showed improved compactness and more uniform particle arrangement, with fewer large voids than the 100 : 0 panel. This intermediate morphology corresponds to the moderate mechanical response observed for this formulation.

The 50 : 50 BPS : WD panel displayed the densest and most cohesive morphology among the tested formulations, with better particle packing and more continuous resin bridging. This morphological trend is consistent with the mechanical results, where the 50 : 50 formulation showed the most favourable overall performance.

3.6 Mechanical–SEM correlation

The mechanical performance trends observed in the mechanical results correspond well with the microstructural features identified through SEM analysis. Across all tests, the overall trend of 50 : 50 > 70 : 30 > 100 : 0 can be related to differences in particle packing density, void formation, and continuity of the interfacial regions. The lower performance of the 100 : 0 panel is consistent with its more porous microstructure, while the better performance of the 50 : 50 panel is supported by its denser morphology and improved structural cohesion.

These observations suggest that improved particle packing and reduced void content were the main contributors to the superior mechanical trend of the 50 : 50 formulation under the selected fabrication conditions.

3.7 FTIR Analysis

The FTIR spectra of all formulations showed the characteristic absorption bands expected for lignocellulosic materials bonded with PF resin. Broad bands in the region around 3300–3400 cm^{-1} were attributed to O−H stretching vibrations associated with hydroxyl groups in cellulose, hemicellulose, and lignin. Peaks near 2900 cm^{-1} correspond to aliphatic C−H stretching, while bands in the re-

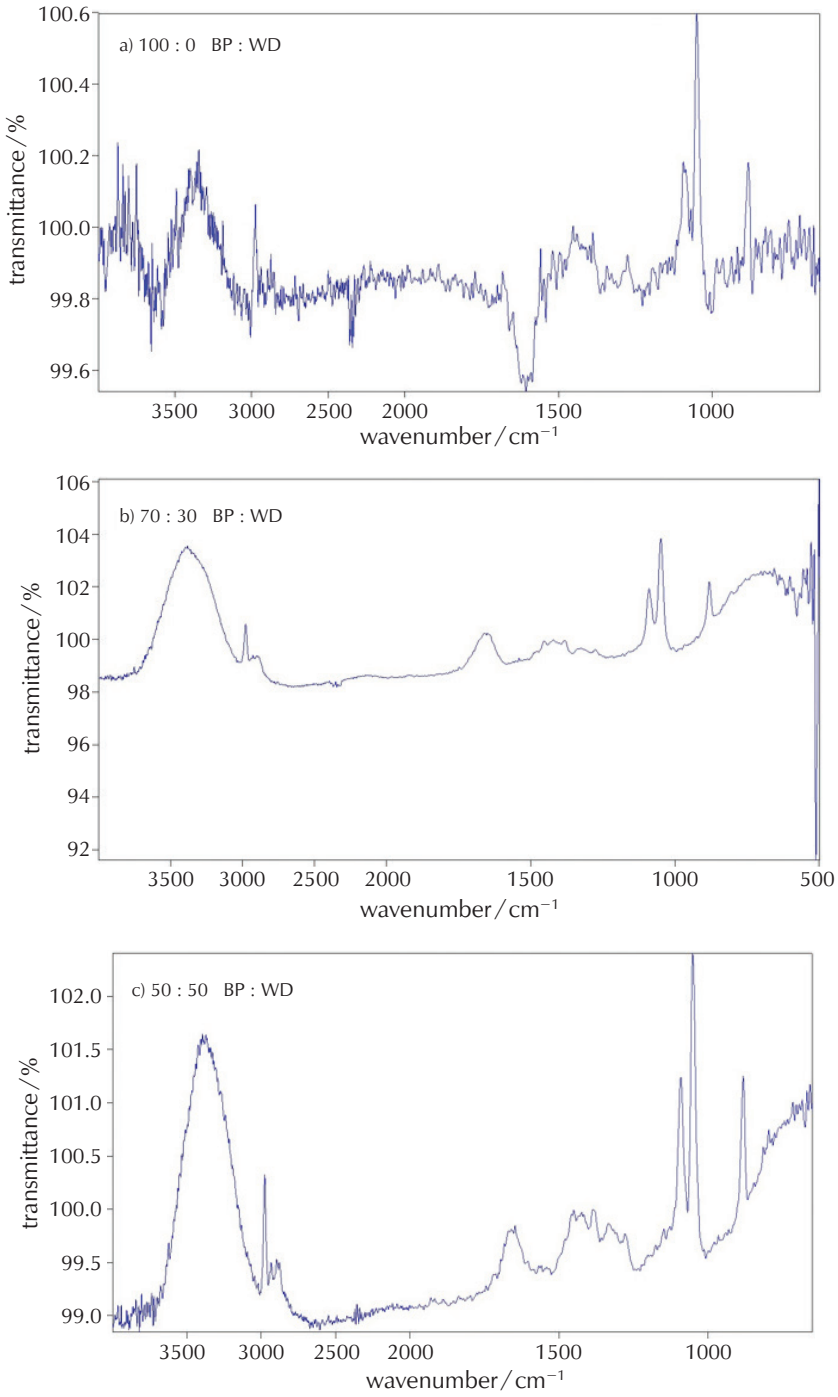


Fig. 13 – FTIR spectra of the fabricated BPS–WD composite panels: (a) 100 : 0, (b) 70 : 30, and (c) 50 : 50

gion around 1000–1100 cm^{-1} are associated with C−O and C−O−C vibrations from polysaccharide structures and resin-related contributions.

Because the three panel formulations are composed of chemically similar lignocellulosic materials combined with the same PF resin system, the FTIR spectra are broadly comparable. Therefore, FTIR is interpreted here as confirming the presence of expected functional groups rather than as a definitive tool for ranking interfacial bonding quality among the samples. The differences in mechanical behaviour are more appropriately discussed on the basis of panel structure, particle packing, void content, and resin distribution as observed in the SEM analysis.

4 Conclusion

This study investigated the fabrication of hybrid composite panels from banana pseudostem (BPS) and wood dust (WD) using phenol-formaldehyde (PF) resin under fixed fabrication conditions. Among the tested formulations, the 50 : 50 BPS : WD panel showed the most favourable overall mechanical trend, supported by SEM observations of a denser and more cohesive morphology. In contrast, the 100 : 0 panel exhibited a more porous structure and weaker overall performance. FTIR confirmed the presence of characteristic functional groups associated with lignocellulosic constituents and PF resin, but its role in the present study is supportive rather than conclusive for explaining mechanical differences. Overall, the findings indicate that hybridisation of banana pseudostem and wood dust can improve composite-panel quality under the selected process conditions. However, due to the limited number of replicates in the present preliminary study, the results should be interpreted cautiously. Further work should include a larger sample size, more complete statistical analysis, and broader property evaluation before stronger conclusions are made regarding application performance.

Author Contributions

Mohd Azril bin Riduan: Investigation, experimental work, data collection, writing – original draft preparation.

Ab Aziz Mohd Yusof: Supervision, review, and technical guidance.

Mohd Jumain Jalil: Conceptualisation, methodology, supervision, writing – review and editing.

Funding Information

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Conflict of Interest Statement

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Industry Relevance

The use of banana pseudostem and wood dust as composite raw materials offers potential for the valorisation of agricultural and wood-processing residues. Under the fabrication conditions applied in this study, hybridisation improved the overall panel behaviour, particularly for the 50 : 50 BPS : WD formulation. These findings suggest possible relevance for low-density, non-structural composite applications. However, broader performance validation and comparison with commercial board requirements are still needed before practical implementation can be fully established.

Statement of Novelty

This study examines the effect of hybridising banana pseudostem and wood dust in different ratios within a PF-bonded particleboard system. The work contributes preliminary insight into how fibre composition influences mechanical behaviour and panel morphology under fixed processing conditions. The combined use of mechanical testing and SEM provides a useful basis for identifying promising formulations for further development.

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SAŽETAK

Razvoj i ispitivanje mehaničkih svojstava iverice proizvedene od stabljike banane i drvne prašine uz primjenu fenol-formaldehidnog veziva

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Sve veća potražnja za održivim materijalima povećala je zanimanje za pretvorbom ostataka iz poljoprivrede i drvoprerađivačke industrije u kompozitne materijale s dodanom vrijednošću. U ovom su istraživanju proizvedene hibridne iverice od pseudostabljike banane (BPS) i drvne prašine (WD), uz primjenu fenol-formaldehidne (PF) smole kao veziva. Pripremljene su tri formulacije, 100 : 0, 70 : 30 i 50 : 50 (BPS : WD), pri jednakim uvjetima proizvodnje, uključujući četverostupanjski ciklus vrućeg prešanja pri 181 °C. Kao glavne metode vrednovanja primijenjena su ispitivanja mehaničkih svojstava i pretražna elektronska mikroskopija (SEM), dok je infracrvena spektroskopija s Fourierovom transformacijom (FTIR) primijenjena kao dopunska metoda za identifikaciju funkcionalnih skupina. Među ispitivanim formulacijama, ploča s omjerom 50 : 50 pokazala je ukupno najpovoljnija mehanička svojstva, s najvišim vrijednostima vlačne, savojne, smične i tlačne čvrstoće, što je potkrijepljeno SEM analizom koja je pokazala gušću i kohezivniju mikrostrukturu. Nasuprot tome, ploča s omjerom 100 : 0 pokazala je slabiju povezanost čestica i porozniju morfologiju. FTIR spektri potvrdili su prisutnost karakterističnih funkcionalnih skupina lignoceluloznih sastavnica i smole, ali su primijenjeni samo kao dopunski dokaz, a ne kao izravna osnova za usporedbu svojstava. Rezultati upućuju na to da kombiniranje BPS-a i WD-a može poboljšati kvalitetu ploča pri odabranim uvjetima proizvodnje. Međutim, budući da ovo istraživanje predstavlja preliminarnu procjenu s ograničenim brojem ponavljanja, dobivene trendove potrebno je tumačiti s oprezom i potvrditi u budućim istraživanjima.

Ključne riječi
Pseudostabljika banane, drvna prašina, fenol-formaldehid, hibridna iverica, mehanička svojstva, SEM, FTIR

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