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Research article

Mechanical and Physical Properties of Binderless Particleboard from Rice Straw and Banana Pseudostem

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Abstract

The commercial particleboards used nowadays are manufactured with synthetic adhesives containing formaldehyde which is considered harmful to health and has a negative impact on the environment. A binderless particleboard fabricated from agricultural waste materials can solve these issues. This research explored the feasibility of using rice straw and banana pseudostem to produce binderless particleboard. The optimal preparation conditions for production were carried out using the ratios of rice straw to banana pseudostem at 100:0, 75:25, 50:50, 25:75 and 0:100, the pressing temperatures of 140°C, 160°C, and 180°C, and the compression times of 10 and 30 min. The physical and mechanical properties of the particleboard including density, moisture content, thickness swelling, modulus of rupture and modulus of elasticity were investigated. Morphological analysis was studied by scanning electron microscopy. It was found that it was possible to produce binderless particleboard from rice straw and banana pseudostem using a hot press method. The results showed that a higher content of banana pseudostem led to good mechanical properties and adhesion with lower thickness swelling. Cross-section of the binderless particleboards revealed that banana pseudostem acted as a binder. Fourier transform infrared spectroscopy (FTIR) also confirmed the occurrence of self-bonding in these binderless particleboards. The optimum preparation conditions were achieved with the ratio of rice straw to banana pseudostem of 0:100, and a pressing temperature of 180°C for 30 min. The modulus of rupture (MOR) and modulus of elasticity (MOE) were approximately 12 MPa and 1800 MPa, respectively. This binderless particleboard is a potential candidate for use in green buildings.

Keywords: binderless particleboard; lignocellulose; rice straw; banana pseudostem

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1. Introduction

Nowadays, particleboard has grown in popularity, particularly in the furniture industry, because of its accessibility, transportability and affordability (The International Market Analysis Research and Consulting Group, 2023). Commercial particleboard is manufactured with synthetic adhesive containing formaldehyde compounds such as urea formaldehyde and phenol formaldehyde. These formaldehyde-based adhesives are harmful to health and the environment. It was found that formaldehyde-based adhesives release vapors harmful to the human body. Exposure to these toxic substances over a prolonged duration may lead to health issues, including the risk of cancer (Tajuddin et al., 2016; Tay et al., 2016; Suradmanee, 2018;). Furthermore, recent growth in the global particleboard market has focused on sustainability and eco-friendly approaches. The selection of raw materials in particleboard production is a crucial factor in achieving a sustainable concept and addressing the issue of toxic adhesives.

Agricultural waste materials are types of lignocellulosic materials, with chemical compositions that include cellulose, hemicellulose, and lignin (Hashim et al., 2012). Lignocellulosic materials can be used to produce binderless particleboard with a self-bonding mechanism (Okuda & Sato, 2004; Nadhari et al., 2019; Vitrone et al., 2021). The self-adhesion processes occur in a complex manner during pre-treatment or hot pressing. There are several explanations for the self-bonding mechanism, including not only chemical reaction such as lignin-furfural linkages, furfural self-polymerization, and condensation reactions in lignin, but also physical phenomena related to lignin softening under heat. These mechanisms depend on the raw materials and production process. Various potential raw materials such as coconut, kenaf core, wheat straw, rice straw, banana bunch, plantain, bamboo, cotton stalks, oil palm and bagasse have been tried in the production of binderless particleboard (Anglès et al., 2001; Fahmy & Mobarak, 2013; Sun et al., 2014; Zhang et al., 2015; Nadhari et al., 2019).

For instance, rice straw binderless particleboard was successfully manufactured by hot-pressing rice straw with particle sizes less than 1 mm. (Kurokochi & Sato, 2015a). Pre-treatments such as hexane extraction for 5 h (Kurokochi & Sato, 2015b) and steam treatment in an autoclave at 200°C, 1.5 MPa for 20 min (Kurokochi & Sato, 2020) were applied to increase self-bonding of binderless particleboard. A mixture of agricultural waste materials for the use as alternatives in binderless particleboard showed promising for the application. For example, rice straw was mixed with bagasse to increase density and improve the mechanical properties of the binderless particleboard (Jamaludin et al., 2020). Another potential raw material is banana plant waste, which is one of the agricultural waste materials suitable for binderless particleboard due to its high percentage of cellulose, holocellulose and lignin. Banana bunches were pretreated in a thermomechanical aqueous vapor process in a batch reactor and used as the raw material for high quality binderless particleboard (Quintana et al., 2009). Banana trunk waste, when subjected to steam pretreatment at 121°C followed by hot pressing, was found to result in better dimensional stability in binderless particleboard (Nadhari et al., 2019).

Thailand is a country with a long agricultural history. Therefore, a lot of agricultural waste is left over after harvesting. Rice straw and banana pseudostem were appealing raw materials for our research due to their abundance, ease of cultivation, and rapid growth. Moreover, these two agricultural wastes cause environmental problems not only in terms of air pollution, including greenhouse gases and fine particulate matter (PM2.5) but also in terms of water pollution (Shah et al., 2005; Barragȧn-Lucas et al., 2019). Rice straw consists of 39.63% cellulose, 35.50% hemicellulose and 13.92% lignin, while banana pseudostem consists of 50% cellulose, 30% hemicellulose and 18% lignin (El-Kassas & Mourad, 2013; Patel & Patel, 2022). With their favorable chemical composition, they can be considered as good candidates for binderless particleboard production. Presently, there is no documented evidence of combining rice straw and banana pseudostem in binderless particleboard production. Our focus lay not only on eco-friendly materials, but also on eco-friendly processes, and utilizing agricultural wastes and employing minimal processing techniques. Therefore, the purpose of our research was to explore the feasibility of using rice straw and banana pseudostem to produce binderless particleboards.

2. Materials and Methods

2.1 Sample preparation

Rice straw was collected from a local area in Ongkharak district, Nakhon Nayok, Thailand, while Banana pseudostem was collected from a local area in Saphan Sung district, Bangkok, Thailand. First, the rice straw and banana pseudostem were cut into small pieces of approximately 2 cm in size. Then, these raw materials were air-dried. The raw materials were subsequently crushed and sieved through a 20-mesh sieve to achieve particle fineness of less than 841 mm and stored in a desiccator. After that, the moisture content of finely crushed raw materials was measured before the mixing process took place. The moisture content of the rice straw was controlled to be not more than 9% while banana pseudostem was controlled to be not more than 14%. The two raw materials were then mixed at the ratios of rice straw to banana pseudostem of 100:0, 75:25, 50:50, 25:75 and 0:100 in a ball mill for 2 h until the mixture was homogeneous.

2.2 Binderless particleboard manufacture

The mold for binderless particleboard used for this experiment was modified by adjusting to dimensions of up to 60 mm in width, 75 mm in length, and 5 mm in depth. The binderless particleboards were then produced by hot pressing in a hydraulic system. Different ratios of rice straw and banana pseudostem were manufactured at pressure of 5 MPa, with different pressing temperatures of 140°C, 160°C, 180°C, and different compression times of 10 and 30 min, as shown in Table 1. The procedure of producing binderless particleboard from rice straw and banana pseudostem is shown in Figure 1.

Table 1. The various conditions of binderless particleboard manufacture

Ratio of Rice Straw:Banana Pseudostem	Pressing Temperature	Compression Times	Pressure
100:0 75:25 50:50 25:75 0:100	140°C, 160°C, 180°C	10, 30 min	5 MPa

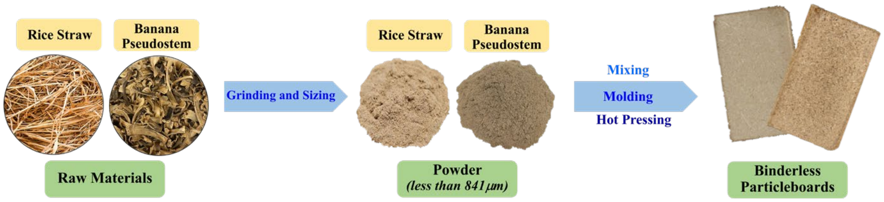

Figure 1. Illustration of the process for manufacturing binderless particleboard using rice straw and banana pseudostem

2.3 Testing

Various mixed rice straw and banana pseudostem binderless particleboards were produced under a range of manufacturing conditions**.** The physical properties, including density, moisture content and thickness swelling of the particleboards were examined. For each condition, six samples were prepared for density and moisture content, while eight samples were prepared for thickness swelling. All physical property testing was repeated three times. The mechanical properties, including modulus of rupture (MOR) and modulus of elasticity (MOE) were also investigated. Five samples were prepared for mechanical properties testing. Additionally, morphological analysis was conducted using scanning electron microscopy (SEM). Chemical structure changes were studied using Fourier transform infrared spectroscopy (FTIR).

2.3.1 Density

Density was determined according to TIS 876-2547. The sample was weighed. The thickness was measured at the center of sample using a micrometer. The dimensions of the sample were measured in width and length using a sliding caliper at a 45-degree angle from the plane. Density was calculated using the following equation (1).

$$Density = \frac{m}{V}\ x\ 10^6 \tag{1}$$

Where m is the mass of the sample (g) and V is the volume of the sample (mm^3).

2.3.2 Moisture content

Moisture content was examined according to TIS 876-2547. Initially, the sample was weighed. Subsequently, the sample was placed in an oven at a temperature of 103±2°C for 15 h. Afterwards, the sample was stored in a desiccator until it cooled down. Finally, the sample was weighed again after drying. Moisture content was calculated using the following equation (2).

$$Moisture\ Content(\%) = \frac{m_1 - m_2}{m_2} \times 100 \tag{2}$$

Where m_1 is the mass of sample before drying in an oven (g) and m_2 is the mass of sample after drying in an oven (g).

2.3.3 Thickness swelling (TS)

Thickness swelling was examined according to TIS 876-2547. The first step involved measuring the thickness at the center of sample. The test was carried out by placing each sample vertically under distilled water at a temperature of 20±2°C for 1 h. The samples were then taken out and excess water was removed with clothes until the sample was almost dry. The sample were left to dry at room temperature for 1 h. After that, the thickness at the same position was measured. Thickness swelling was calculated using the following equation (3).

$$Thickness\ Swelling(\%) = \frac{t_2 - t_1}{t_1} \times 100 \tag{3}$$

Where t_1 is the thickness at the center before immersion in distilled water (mm) and t_2 is the thickness at the center after immersion in distilled water (mm).

2.3.4 Modulus of rupture (MOR) and modulus of elasticity (MOE)

Modulus of rupture and modulus of elasticity were investigated in accordance with ASTM-D790. MOR and MOE were determined using a three-point bending flexural test. The dimensions of the test specimens were 34 mm in width, 60 mm in length, 44 mm span and 1.5 mm in depth. The samples were tested at a cross-head speed of 1 mm/min using a universal testing machine.

2.3.5 Morphological analysis

Morphological analysis was conducted using a scanning electron microscope (Thermo Scientific™ Prisma E). The binderless particleboard samples were cut into square pieces with dimensions of 1 cm in width. These samples were then attached to aluminum stubs using carbon tape. After that, the samples were coated with gold and observed for both surface and cross-sectional areas.

2.3.6 Chemical analysis

The chemical structure changes of the functional groups of the binderless particleboard samples were studied using Bruker ALPHA II FTIR Spectrometer. The scanning range was 550-4000 cm^{-1}, and the sample scan time was 24 scans. The attenuated total reflectance (ATR) method was used.

3. Results and Discussion

3.1 Physical properties of mixed rice straw and banana pseudostem binderless particleboards

The density values for rice straw and banana pseudostem binderless particleboards at various ratios, pressing temperatures and pressing times are presented in Table 2. The density of these binderless particleboards ranged from 932 to 1080 kg/m^3, exceeding the Thai Industrial Standard (TIS 876-2547) range of 400-900 kg/m^3. The ratio of rice straw

Table 2. Density of mixed rice straw and banana pseudostem binderless particleboard under various conditions

	Density (kg/m^3)					
Processing Parameter	**140°C**		**160°C**		**180°C**	
	10 min	**30 min**	**10 min**	**30 min**	**10 min**	**30 min**
Ratio of 100:0	986.63±51.45	956.00±50.88	1006.85±42.76	939.05±80.66	982.71±65.80	939.02±55.53
Ratio of 75:25	1004.40±4.76	1000.72±29.70	1025.71±13.84	1007.22±27.38	1020.03±69.18	981.53±14.37
Ratio of 50:50	1050.12±10.50	992.94±51.14	1035.43±72.66	992.34±45.56	984.70±42.16	986.16±51.16
Ratio of 25:75	1001.29±23.77	1013.37±5.97	1026.51±50.04	1001.94±33.00	987.15±61.64	932.20±32.98
Ratio of 0:100	1080.89±2.44	1045.27±22.72	1030.51±53.40	1035.44±17.17	1023.84±19.24	986.89±15.82

(Ratio of Rice Straw: Banana Pseudostem)

and banana pseudostem, as well as pressing temperature and pressing time, did not exhibit significant differences.

The moisture contents of rice straw and banana pseudostem binderless particleboards at various ratios, pressing temperatures and pressing times are shown in Table 3. Both pressing temperature and time significantly influenced the moisture content of the mixed rice straw and banana pseudostem (ratio of 75:25, 50:50 and 25:75). Higher pressing temperatures and longer pressing times produced lower moisture content. Pure rice straw and banana pseudostem did not show significant differences in the same manner. This may have been due to their own raw materials characteristic (Astari et al., 2019). However, the binderless particleboards manufactured from pure rice straw or banana pseudostem exhibited moisture contents within the range specified by the Thai Industrial Standard (TIS 876-2547), ranging from 4 to 13 %.

The binderless particleboards made from rice straw and banana pseudostem exhibited lower thickness swelling at higher banana pseudostem content, increased pressing temperature, and longer pressing time, as illustrated in Figure 2. The lowest thickness swelling observed for these binderless particleboards was approximately 30%, significantly higher than the Thai Industrial Standard, which specifies a maximun of 12%. However, based on the results, the optimal pressing temperature and time were found to be 180°C and 30 min, respectively. At elevated pressing temperatures, the primary chemical component, specifically lignin, likely melts and acts as a binder, holding the particles together (Homkhiew et al., 2017; Börcsök & Pásztory, 2021). A higher percentage of lignin is expected to enhance bonding strength and dimensional stability including thickness swelling. During the hot-pressing process, lignin can flow when the pressing temperature exceeds the glass transition temperature of lignin, increasing mechanical contact between particle surfaces (Boon et al., 2017; Hubbe et al., 2018; Vitrone et al., 2021). Remarkably, banana pseudostem contains higher lignin content than rice straw. Consequently, the results of different ratios of rice straw to banana pseudostem indicated that the thickness swelling decreased as the amount of banana pseudostem increased.

Table 3. Moisture content of mixed rice straw and banana pseudostem binderless particleboard under various conditions

	Moisture Content (%)					
Processing parameter	**140 °C**		**160 °C**		**180 °C**	
	10 min	**30 min**	**10 min**	**30 min**	**10 min**	**30 min**
Ratio of 100:0	4.43±0.66	4.40±0.43	4.14±0.48	4.43±0.23	4.96±0.06	4.98±1.15
Ratio of 75:25	3.26±0.75	2.93±0.72	2.22±0.97	1.80±1.12	1.91±0.32	1.72±0.37
Ratio of 50:50	3.79±0.66	3.02±0.64	2.32±0.40	2.46±0.77	2.50±1.37	2.05±0.45
Ratio of 25:75	5.62±0.40	4.71±0.35	3.88±0.04	2.98±0.32	2.41±0.40	1.69±0.35
Ratio of 0:100	6.94±0.98	6.22±0.95	4.43±0.73	4.66±1.38	3.72±1.75	2.89±1.68

(Ratio of Rice Straw: Banana Pseudostem)

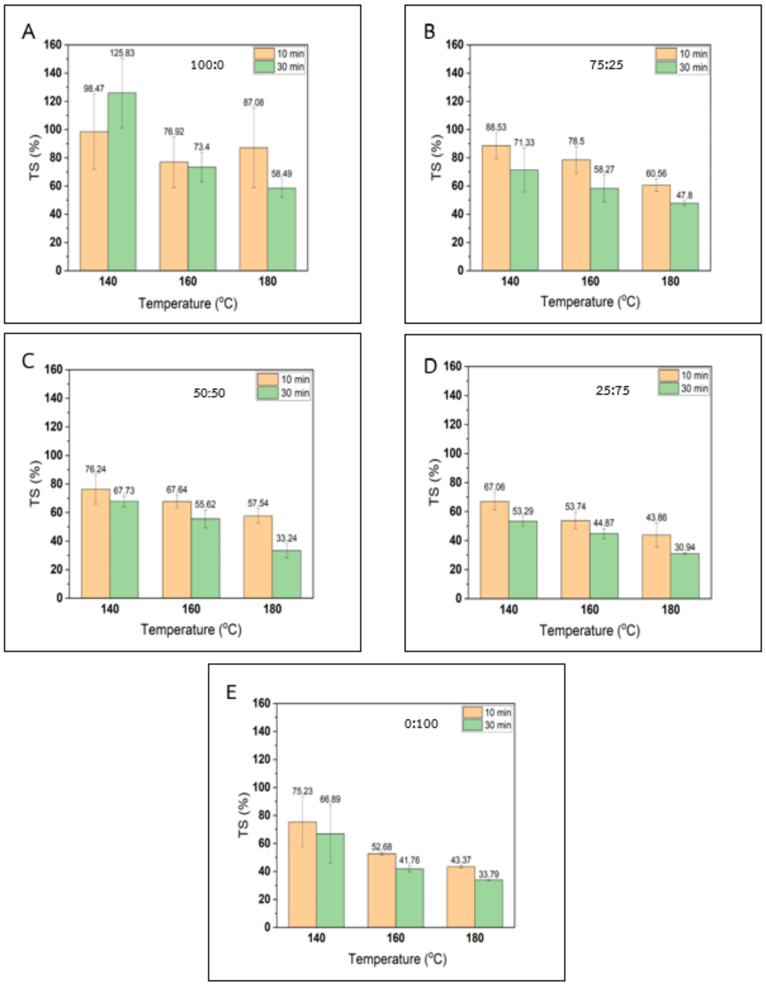

Figure 2. Thickness swelling of mixed rice straw to banana pseudostem at different mixed ratios of (A) 100:0 (B) 75:25 (C) 50:50 (D) 25:75 and (E) 0:100, with different pressing temperatures (140°C, 160°C, 180°C) and different compression times (10, 30 min)

3.2 Mechanical properties of mixed rice straw and banana pseudostem binderless particleboards

The modulus of rupture (MOR) and modulus of elasticity (MOE) of mixed rice straw and banana pseudostem particleboards under various conditions were determined. Overall, all factors, including the ratio of rice straw and banana pseudostem, pressing temperatures and pressing time, did not produce significant differences in the modulus of rupture. However, some cases were notable. For instance, in the MOR results for 160°C for 30 min shown in Figure 3 (left), it was observed that the ratios of 100:0, 75:25, 25:75 and 0:100 had similar MOR values of 11.82, 11.06, 11.35 and 11.37 MPa, respectively. However, at the ratio of 50:50, the MOR value was lower at 9.74 MPa. The difference may be attributed to an uneven distribution of raw materials during mixing, resulting in a lower MOR compared to other ratios.

For modulus of elasticity results, the ratio of rice straw and banana pseudostem significantly affected MOE due to the characteristics of raw materials. For example, the MOE results at 160°C for 30 min shown in Figure 3 (right) indicated that the ratios of 100:0, 75:25 and 50:50 had similar modulus of elasticity values of 1443.33, 1483.33 and 1373.33 MPa, respectively. This similarity can be attributed to the higher content of rice straw than banana pseudostem at these ratios, resulting in the presence of powder particles mixed with fibres. This uneven distribution may have also contributed to the test particleboard having a lower modulus of elasticity than the particleboard at other ratios, as the presence of fiber can interfere with adhesion. These contrast with the 25:75 and 0:100 ratios, which exhibited higher modulus of elasticity values of 1743.33 and 1760 MPa, respectively. At these ratios, the amount of banana pseudostem was higher than that of rice straw, indicating that effective self-bonding occurred during the hot pressing process. The higher content of cellulose and lignin in banana pseudostem might lead to better mechanical properties. Moreover, the particles presence at higher content of banana pseudostem were uniform and this might lead to better dispersion and adhesion (Nadhari et al., 2019; Nitu et al., 2020; Homkhiew et al., 2021). The binderless particleboards made from rice straw and banana pseudostem exhibited good mechanical properties, especially at higher banana pseudostem content. The optiamal condition was found for the rice straw and banana pseudostem ratio of 0:100, which had MOR and MOE values of 11.37±0.81 MPa and 1760.00±147.31 MPa, respectively. These binderless particleboards almost met the standards outlined in the European standard for particleboard (EN 312, 2005). The minimum modulus of rupture (MOR) for particleboard used in general applications, and for panels for furniture production and interior equipment purposes were set at 12.5 MPa and 13 MPa, respectively. Meanwhile, the minimum modulus of elasticity (MOE) for interior fittings (including furniture) was specified as 1800 MPa (EN 312, 2005; Bardak et al., 2019). Moreover, our binderless particleboards met the requirements of the Chinese national standard for particleboard (GB/T 4897-2015, 2015). The minimum modulus of rupture (MOR) was established at 10.5 MPa for particleboard utilized in general applications and 11 MPa for furniture-grade particleboard. Additionally, furniture-grade particleboard must meet a minimum modulus of elasticity (MOE) requirement of 1800 MPa (GB/T 4897-2015, 2015; Chen et al., 2023).

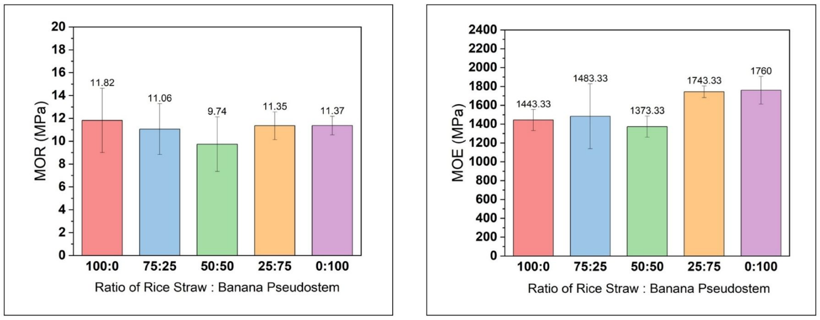

Figure 3. MOR and MOE of mixed rice straw to banana pseudostem with different mixed ratio at 100:0, 75:25, 50:50, 25:75, 0:100 and pressed at 160°C for 30 min

3.3 Morphological analysis of mixed rice straw and banana pseudostem binderless particleboards

The SEM cross-section images of the mixed rice straw and banana pseudostem binderless particleboard confirmed that certain parameters particularly the ratio of rice straw and banana pseudostem and pressing temperature, might affect the mechnical properties as well as the physical properties, specifically the thickness swelling, of the particleboard.

Different ratios of rice straw to banana pseudostem binderless particleboard at the ratios of 100:0, 50:50 and 0:100 are shown in Figure 4. At the ratios of 100:0 and 50:50, similar appearances were observed, revealing large elongated structures that resulted in poor adhesion as shown in Figure 4 (A) and 4 (B) respectively. Meanwhile, at the ratio of 0:100, the banana pseudostem particles resembled powder particles and were of a smaller size than those of rice straw. This could lead to better compaction resulting in good adhesion and fewer gaps as shown in Figure 4 (C). Thus, the distribution of raw materials significantly affected adhesion and mechanical properties.

The results of the comparison of pressing temperatures at 140°C, 160°C, 180°C for 30 min, with a ratio of rice straw to banana pseudostem at 50:50, are presented in Figure 5. For the temperature of 140°C, as illustrated in Figure 5 (A), the cross-section images revealed poor adhesion and wide gaps between particles for both types of raw materials. The similar evaluation conducted at 160°C, shown in Figure 5 (B), demonstrated that the powder particles of both raw materials had melted, resulting in better adhesion and reduced spacing between particles. This improvement can be attributed to lignin softening at temperatures of 138-160°C (Homkhiew et al., 2016). Furthermore, when compared to a temperature of 180°C, as depicted in Figure 5 (C), the cross-section images show that the powder particles of both types of raw materials were compacted until they became almost uniform, which likely led to strong adhesion between particles. Additionally, the gaps between the particles were hardly visible. According to the results of thickness swelling, with increasing temperature, the thickness swelling value of the test particleboard decreases. This was due to the enhanced adhesion, making it more difficult for water to be absorbed.

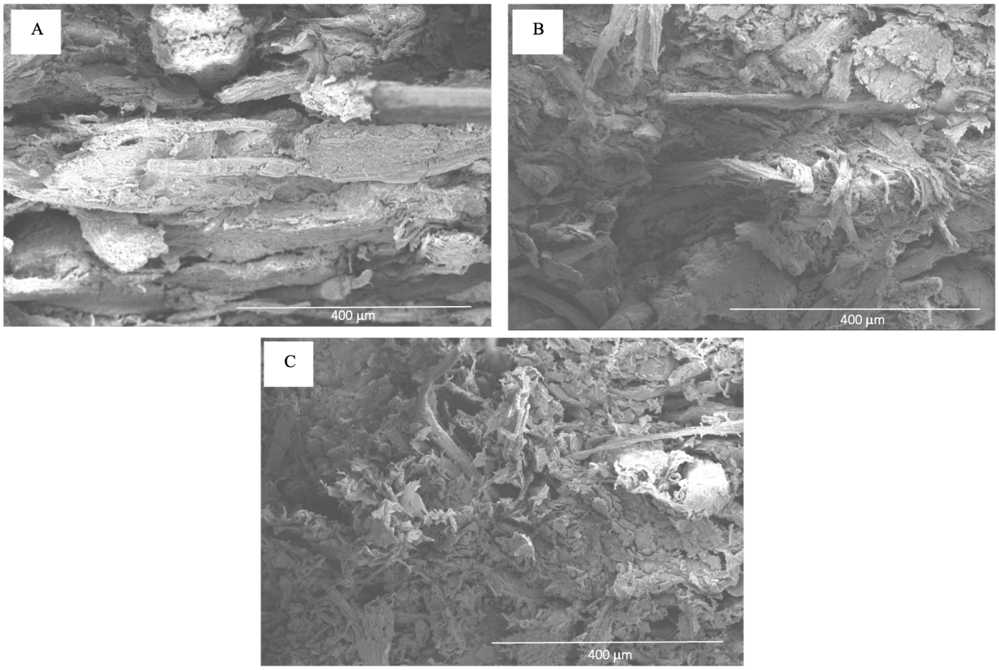

Figure 4. SEM images of mixed rice straw to banana pseudostem particleboards pressed at different ratios of (A) 100:0 (B) 50:50 and (C) 0:100, with pressing temperature of 160°C for 30 min

3.4 Chemical analysis of mixed rice straw and banana pseudostem binderless particleboards

Chemical structural changes of the binderless particleboards under various conditions were observed. As mentioned above, key processing parameters, including pressing temperature and pressing time, affected the physical and mechanical properties of the binderless particleboards. The mechanism of self-bonding of the binderless particleboards can explain these effects. Figure 6 shows the infrared spectra of the mixed rice straw and banana pseudostem particleboards pressed at the different pressing temperatures for 30 min with a mixing ratio of 50:50. The spectra reveal a wide band near the 3325 cm^{-1}, representing the stretching vibration of O-H bonds in cellulose, hemicellulose and lignin. The peak intensity decreases at temperatures exceeding 140°C, indicating the weakening of H-bonding and the elimination of hydroxyl groups and resulting in lower thickness swelling. The band at 2917 cm^{-1} indicates the presence of aliphatic C-H stretching in cellulose and hemicellulose. The peak at 1620 cm^{-1} can be attributed to the C=C bond in benzene rings, characteristic of aromatic lignin, while the peak around at 1314 cm^{-1} represents the bending vibration of C-H and C-O bonds in cellulose, hemicellulose and lignin. The peak intensities of the binderless particleboards at 1620 cm^{-1} and 1314 cm^{-1} decreased at pressing temperatures of 160°C and 180°C compared to those at 140°C. This suggests that cellulose and hemicellulose might undergo hydrolysis, producing some sugars and degrading into furfurals during hot pressing at specific pressing temperatures.

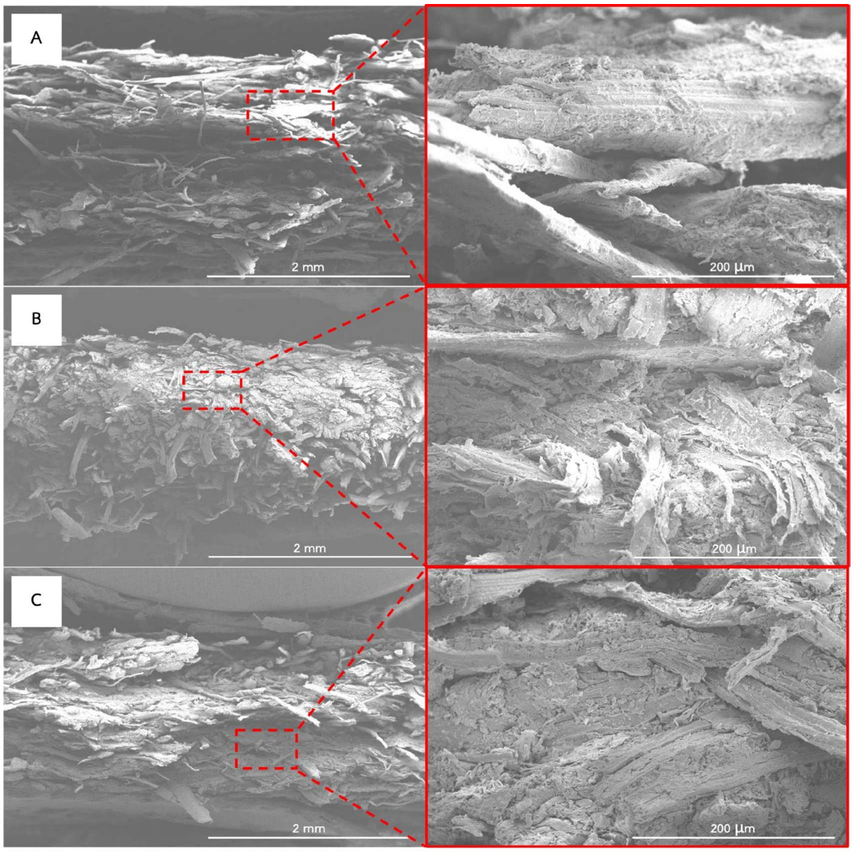

Figure 5. SEM image of mixed rice straw to banana pseudostem particleboards pressed at pressing temperatures of (A) 140°C (B) 160°C and (C) 180°C for 30 min with a mixing ratio of 50**:**50

Subsequently, furfural condensation with lignin probably led to the occurrence of self-bonding in the binderless particleboard, strengthening the particleboards. The strong and sharp peak at 1026 cm^{-1} indicates the presence of C-O-C stretching in the pyranose ring skeletal structure. The decreased intensity at pressing temperatures of 160°C and 180°C, compared to 140°C, implies that polysaccharides might contribute to the improvement of bonding properties (Cecci et al., 2019; Nadhari et al., 2019; Shrestha et al., 2021; Badanayak et al., 2023; Chen et al., 2023). In a similar manner in terms of pressing time, as shown in Figure 7, the infrared spectra illustrated the mixed rice straw and banana pseudostem particleboards pressed at 180°C for 10 and 30 min with a mixing ratio of 50:50.

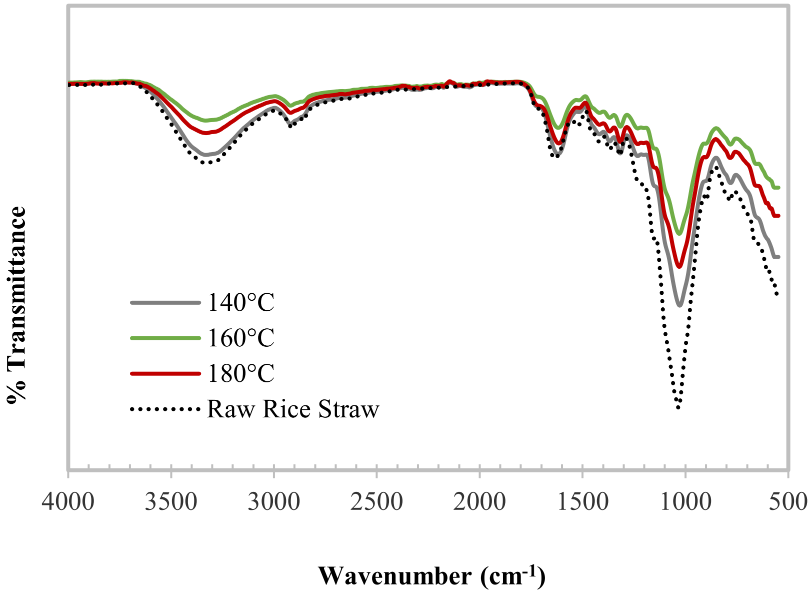

Figure 6. The infrared spectra of the mixed rice straw and banana pseudostem particleboards pressed at the different pressing temperatures for 30 min with a mixing ratio of 50:50

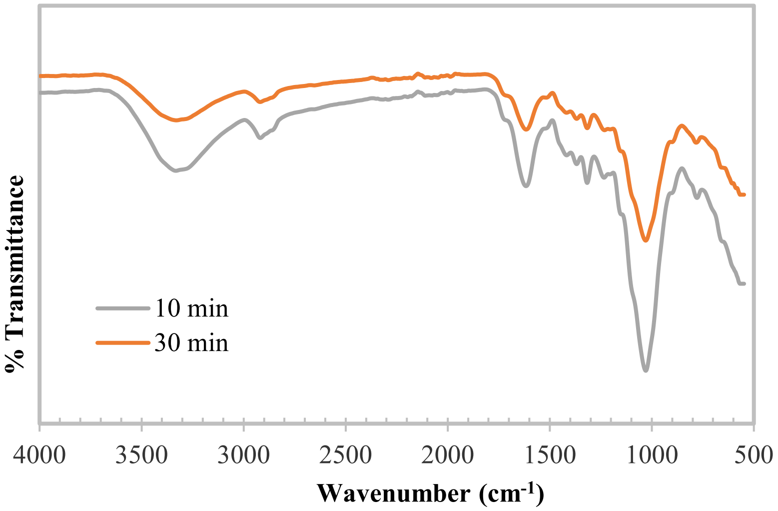

Figure 7. The infrared spectra of the mixed rice straw and banana pseudostem particleboards pressed at 180°C for 10 and 30 min with a mixing ratio of 50:50

4. Conclusions

Agriculture waste from rice straw and banana pseudostem demonstrated the feasibility of manufacturing binderless particleboards via hot pressing method. The mixed rice straw and banana pseudostem binderless particleboard types were produced under various conditions and then investigated for their physical and mechanical properties. The ratios of the two raw materials and the processing parameters, including pressing temperature and pressing time, had an influence on the properties of binderless particleboards, particularly the moisture content, thickness swelling, and modulus of elasticity. Good mechanical properties and adhesion with lower thickness swelling were obtained by using a higher content of banana pseudostem at higher pressing temperature and longer pressing time, i.e., 180°C and 30 min. The changes in the functional group structure of the binderless particleboard could clarify the self-bonding mechanism. Compared to the particleboard standard, the physical properties such as density and moisture content of the experimental board fell within the range of Thai standard, while thickness swelling needed improvement to meet the standard. Meanwhile, the mechanical properties of binderless particleboards in our study were not far from meeting the criteria set by the European standard for particleboard and fulfilling the specification of the Chinese standard for particleboard, which is applicable for both general purposes and for furniture. Our binderless particleboard embodies a green concept throughout its life cycle, from the raw material stage throughout the manufacturing process. The green particleboard is a sustainable material and seems to be an excellent green candidate for use in environmentally-friendly furniture and interior decoration. Two considerations for future work should be noted. Firstly, the manufacturing process needs to be scaled up to match the dimensions of real-world applications and the possibility of production in small and medium community enterprises should be explored. Secondly, properties with particular attention on thickness swelling need to be improved while prioritizing an eco-friendly focus.

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6. Conflicts of Interest

There is no conflict of interest.

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