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Effects of Refining Parameters on the Properties of Oil Palm Frond (OPF) Fiber for Medium Density Fibreboard (MDF)

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ABSTRACT

Studies on the manufacture of medium density fiberboard (MDF) from oil palm frond (OPF) fibre were conducted to provide a sustainable and feasible source of lignocellulosic materials. The quality and properties of the fibre are very important as it dictates the final MDF properties. The properties of fibre like fibre pH, buffering capacity, and morphology can influence most of the MDF performances. Refining condition is one of the most important factors which determine the properties of the refined fibre. In this study, the effects of different refining pressures and temperatures on OPF fibre were evaluated. The refining of OPF fibre was observed at four levels of refining parameters; which were categorized as low (2 bar at 130 °C), medium (4 bar at 150 °C), high (6 bar at 170 °C), and severe (8 bar at 190 °C). The refining heating time of 5 minutes was employed. The pH, buffering capacity, morphology, and the surface of the fibres were evaluated. The refined fibres were used to manufacture fibreboard panels at a target density of 720 kg/m^3 and 12% urea formaldehyde (UF) resin. The panel's physical (thickness swelling) and mechanical properties (bending and internal bonding strength) were then evaluated according to European Standard (EN 622-5, 2006). The results indicated that refining conditions affected the properties of the fibres and final boards. High steam pressure and temperature-induced pH changes in OPF fibres, leading to more acidic fibres and greater acid buffering capacity. The fibre separation was more adequate at this level and produced fibre with a smooth surface. Based on the test results for fibreboard properties, high steam pressure and temperature produced better dimensional stability of panels and bending and bonding strength. However, at the highest refining condition (severe level), the board performances began to deteriorate. The best performances of the samples were found for the panels made under refining conditions of 6 bar at 170 °C.

Keywords:
Buffering capacity; medium density fibreboard (MDF); fibrillation; acidic fibre

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1. Introduction

Oil palm (*Elaeis guineensis*) is considered one of Malaysia's main cultivated plants, which produces millions of tons of waste every year. In terms of plantation and cultivation, and processing in oil palm mills, the palm oil industry generates a huge amount of agricultural waste, estimated at 135 million tonnes annually [1]. The waste includes a large number of lignocellulosic sources such as empty fruit bunches (EFB), oil palm trunks (OPT), oil palm fronds (OPF), palm kernel shell (PKS), palm oil mill effluent (POME) and pressed mesocarp fibre (PMF). Awalludin *et al.,* [2] estimated that nearly 75% of oil palm wastes were left after harvesting or replantation in the form of OPT and OPF, and 36 million tonnes were left after oil processing from EFB [3]. In 2020, with an oil palm plantation area of 5.86 million hectares, it had generated more than 120 million tonnes of oil palm biomass, consisting of (in tonnes/hectare) 20.08 EFB, 74.48 OPT, 14.47 OPF and 1.10 PKS [4].

The oil palm biomass wastes can be utilised in many applications such as plywood [5-6], fibreboard [7-11], particleboard [12-13], biofuel [14-15], plastic and polymer composites [16-20], nanocomposite [21-22], pulp and paper [23-24], drilling mud [25] and laminated veneer lumber (LVL) [26]. The utilisation of oil palm wastes into value-added products was initially due to the shortage of wood sources, the accumulation of the wastes, and good fibre quality offered by these types of biomass. Each oil palm waste has different properties and characteristics in all aspect ratios such as physical, chemical, mechanical, and anatomical. For instance, EFB fibre contains a low amount of lignin. Thus, EFB is suitable for pulp and paper production. On the other hand, OPT fibre was found to have the thickest S2 layers of 3.43 µm, which provided better fibre strength due to the cellulose microfibrils in line with that layer's fibre axis [27-28]. The utilisation of oil palm biomass in MDF production is shown in Table 1.

OPF contain higher contents of holocellulose (83.5%) and α-cellulose (49.8%) but lower lignin content when compared to OPT, EFB and OPS [28-35]. This makes it suitable to be used as a reinforcement material. Several studies have been conducted and explored in utilising OPF fibres for conversion to various products. Yusoff *et al.,* [24] and Ona *et al.,* [35] found that OPF shows high tensile and tear indices due to its relatively long fibres (1.59 mm) and lower levels of extractives as compared to softwood fibre. Hashim *et al.,* [13] manufactured and evaluated the properties of binderless particleboard from OPF and showed that the boards have a high Modulus of Rupture (MOR) value of 8.45 MPa due to the fact that it contains high hemicellulose, thus creating an enhanced bonding between particles and resulting in good bending properties. The integration of OPF and clay particles into the reinforcement of high-density polyethylene (HDPE) under various treatments has been studied by Hamid Essabir *et al.,* [18]. The study showed that the alkali of OPF fibres improved their surface interaction with HDPE and the hybridization of the two materials, in which Young's modulus experienced an incremental increase of 49% and tensile strength by 11%.

Fibreboard is manufactured from fibres resulting from pulping and refining processes by converting biomass materials to fibres through several methods to break down the bulk structure into fibre sources [36]. One practical pulping method is thermo-mechanical pulping (TMP), by processing biomass using heat and a mechanical refining movement. This method involves steaming the materials at certain steam pressure (related to steam temperature) for a short period prior to and during refining. This process, which generates heat and water vapour and softens the lignin, is followed by mechanical force or refining by crushing or grinding, thus separating the individual fibres. TMP refining impacts significantly on the overall fibre properties. During a typical TMP process, steam pressure, temperature, and time are the key parameters that affect the fibre properties, thus affecting almost all MDF panel properties.

Table 1
List of utilisations of oil palm biomass fibre for the production of MDF

Fibre	Study Summary	Key Findings	Reference
Oil Palm Trunk (OPT)	Study on MDF properties made from OPT as affected by refining pressure (2, 4, 6 and 8 bar) and preheating time (100, 200, 300 and 400 seconds).	OPT fibre treated at 8 bar produced good swelling resistance but detrimental to the board's mechanical properties. 6 bar steam pressure offered the highest value of mechanical properties, while intermediate refining condition was found the better board properties.	[7]
Oil Palm Empty Fruit Bunches (EFB)	Study on the utilisation of the EFB fibres in MDF production.	The presence of residual oil in EFB fibre effect bonding and finished properties in MDF.	[29]
Oil Palm Empty Fruit Bunches (EFB)	Treated EFB fibre with two methods of pre-treatment : boiling in the water and soaking in 2% of NaOH for 30 minutes for MDF making.	Pre-treated with NaOH removed more oil than water boiling. In the MDF properties, the panels from water boiling performed better than panel from NaOH due to the poorer fibre with a higher bulk density that reduced the mechanical and physical properties of the panels	[30]
Oil Palm Empty Fruit Bunches (EFB)	Study on the properties of MDF from EFB and rubberwood (RW) fibre.	MDF made from oil palm EFB had many inferior properties compare to those made from rubberwood	[9]
Oil Palm Empty Fruit Bunches (EFB)	Treatment on EFB fibre for MDF making and use phenol-formaldehyde resin as a matrix.	The modification of the treated EFB fibre with acetic and propionic anhydride improved the Internal Bonding (IB) strength of the MDF due to the better compatibility between the matrix resin surface and increasing of the hydrophobic properties of the fibre.	[31]
Oil Palm Empty Fruit Bunches (EFB)	Study on the effects of storage time and relative humidity of MDF made from RW and EFB fibres by measuring the changes of the board mechanical and physical properties.	At 65% humidity, MDF exhibited a lower effect on the mechanical and physical properties of the panel, whereas, at 93% humidity, the panel exhibited a decrease in the dimensional stability and mechanical properties of the board.	[32]
Oil Palm Empty Fruit Bunches (EFB)	Evaluation of properties of MDF from treated EFB fibre. The EFB fibre was subjected to the different types of treatments : soaking in 2% of NaOH, boiling in the hot water, and combining soaking in the NaOH and boiling.	For mechanical properties, the boiling method produced MDF with better properties attributed to the increase in the extent of crystallinity and reduction in the amorphous region during boiling. In dimensional properties, the boiled-treated MDF was the lowest due to the degradation of hemicellulose and lignin in the fibre during boiling treatment.	[8]
Oil Palm Empty Fruit Bunches (EFB)	Assessment on the effect of NaOH and acetic acid treatment at different concentration levels on the morphological structure of oil palm empty fruit bunches (EFB) fibres.	Both treatments had successfully removed the residual oil, with NaOH treatment removing more oil than acetic acid treatment. However, both treatments resulted in different surface characteristics. The acid treatment resulted in rougher fibre surface and more removal of silica bodies. The acetic acid treatment led to better surfaces than NaOH.	[33]
Oil Palm Empty Fruit Bunches (EFB)	The properties of MDF made from EFB fibres were investigated as a result of chemical treatments. (NaOH and acetic acid concentrations of 0.2, 0.4, 0.6, and 0.8%).	Both treatments resulted in varying MDF performances, with acetic acid fibre having stronger bending and bonding properties. To manufacture panels with reasonable strength and dimensional consistency, the optimal conditions of chemical used for NaOH is 0.4%, and acetic acid is 0.6%.	[34]

Several studies have indicated that refining parameters during TMP can influence the performance of MDF. Mild refining condition produced roughness and longer fibre, which resulted in higher dimensional stability and better mechanical properties of MDF. Meanwhile, severe refining condition produced shorter fibre and a higher percentage of broken fibre, resulting in poor physical properties of MDF [37-38]. In addition, Nayeri *et al.,* [39] (2013) and Nayeri *et al.,* [40] (2014) concluded that the refining parameter influenced the permeability of the matrix in the fibre network of the board. Furthermore, Halvarsson *et al.,* [41] and Passialis *et al.,* [42] also stated that fibre acidity and buffering capacity of TMP refined fibres vary between biomass components, raw materials, steam pressure, and temperature. Fibre acidity and buffering capacity are key factors when bonding the fibres with adhesives as it affects the cure of the resin. Thus, this study investigated the potential of OPF as raw materials under different refining conditions (steam pressure and steam temperature) for MDF by assessing the pH, buffering capacity and morphology of the fibres, and micrograph images of the refined fibres. The refined fibres were used for the manufacturing of fibreboard. Dimensional stability and mechanical properties were also analysed in this study.

2. Experimental

2.1 Raw Materials and Preparation of Samples

Oil palm biomass in the form of fronds used in this study was obtained from a local palm oil plantation. Before refining, the fronds were chipped using a chipper to reduce their size and air-dried for 24 hours. TMP then processed the fronds at the MDF pilot plant located in MPOB/UKM Research Station. The pulping process was carried out in an inclined stainless-steel digester (Sprout-Bauer, ANDRITZ) built-in with a computer-controlled thermocouple. The chipped fronds were treated with four different steam pressures (2, 4, 6, and 8 bar) and steam temperatures (130, 150, 170, and 190 °C), using a digesting time of 5 minutes additional chemicals were used in this study. The variables of refining conditions are shown in Table 2. After the refining process, the fibres were oven-dried until they reached a 4-5% moisture content. Figure 1 shows the oil palm (a) fronds, (b) chips, and (c) fibres.

Table 2
The refining conditions of oil palm frond chips

Refining Condition	Steam Pressure (bar)	Steam Temperature (°C)
Low	2	130
Medium	4	150
High	6	170
Severe	8	190

Note: The refining conditions during the thermo-mechanical pulping (TMP) process, with a digesting time of 5 minutes

Fig. 1. The conversions from oil palm (a) fronds, (b) chips, and (c) fibres

2.2 Determination of Fibre Properties

The pH value and buffering capacity were determined by preparing OPF extract solutions. About 25 g of OPF fibres were refluxed in 250 mL distilled water at a temperature between 70-80 °C for 20 minutes on a hot plate and filtered with filter paper. When the solution reached a temperature of 20 °C, the filtered solution was cooled. Then, the aqueous extraction solutions were used for pH calculation and were titrated using 0.1 N hydrochloric acid (HCl) to pH 3 to measure acid buffering capacity. Moreover, 0.1 N sodium hydroxide (NaOH) was utilised until pH 11 was achieved to calculate its capacity for alkaline buffering.

The fibres length and width were measured using a stereo microscope attached with an image analyzer (Model Quantiment 520 with Leica Camera Model MPS32). Approximately 100 fibres were randomly collected from each refining condition, and their length and width dimensions were measured. The aspect ratio or the length-to-width ratio was calculated. Hitachi 3400 optical Scanning Electron Micrograph (SEM) was used to observe the surface of the refined fibres. SEM micrographs were taken to investigate the surface condition of the refined fibres. All samples were sputter-coated with gold at an acceleration voltage of 15 kV to avoid charging.

2.3 Production of Fibreboard from OPF Fibres and Testing

For each refining condition, four boards were manufactured with a total of sixteen single layers of fibreboard, with board dimensions of 300 mm × 300 mm and thickness of 12 mm. The density of the boards was targeted at 720 kg/m^3, and the refined fibre was blended with 12% of urea formaldehyde (UF) resin with 65% of solid content. The single layer mats were formed manually and were cold-pressed, followed by compression in a computer-controlled hot press with different pressure settings for 5 min using a pressing temperature of 180 °C. The boards were conditioned in the conditioning room for 24 hours at a temperature of 23±2 °C and relative humidity of 65±5% prior to the testing.

For thickness swelling (TS) determination of each board, five test specimens of 50 mm to 50 mm were prepared. The TS was determined at 4 points in the test specimens by calculating the thickness. The specimens were then submerged in distilled water for 24 hours. The thickness measurement was taken at the same points after immersion, and the TS value was calculated. Static bending specimens with a length of 200 mm were cut into 200 mm x 50 mm x actual thickness. A three-point bending test was carried out using a universal tester (Zwick 10 kN) at a 10 mm/min crosshead speed, based on the European Standard (EN 310). 10 specimens were tested for each board to determine the average rupture modulus (MOR) and elasticity modulus (MOE) values. The samples' size was 50 mm x 50 mm x the actual thickness for the internal bonding (IB) test. The specimen was measured at a 7 mm/min crosshead speed using the European Standard (EN 319).

3. Results and Discussion
3.1 Fibre Properties

Table 3 shows the pH values of OPF fibres after the TMP process. The results showed that the pH values were distinctly higher (less acidic) when refined at lower steam pressures than that of OPF fibres refined under higher steam pressures. The pH values of OPF fibres generally decreased as more severe TMP conditions were applied. The changes in pH values varied among the different steam pressures related to the changes of some chemical constituents such as extractives contents, acidic groups in hemicellulose, and organic acid, as these substances are responsible for the acidity of fibres.

Rowell [43] stated that the amount of hemicellulose and lignin contents has a higher availability of acidic groups, thus contributing to the level of acidity of the fibres.

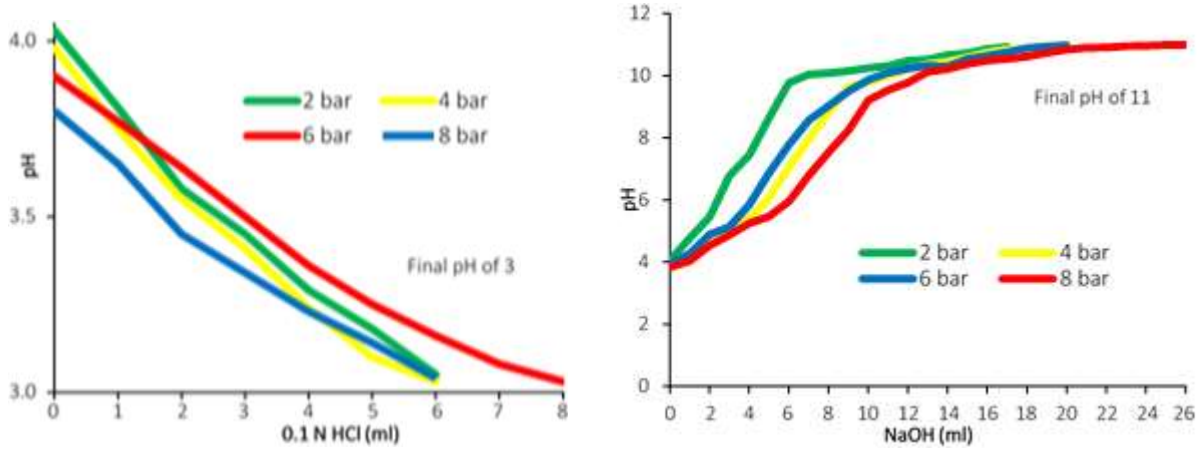
Table 3
pH values of refined oil palm frond (OPF) fibres

Refining Condition	Steam Pressure (bar)	Steam Temperature (°C)	pH Value
Low	2	130	4.07 ^{a}
Medium	4	150	3.96 ^{b}
High	6	170	3.94 ^{b}
Severe	8	190	3.83 ^{c}

Note: The means figure followed by the same letters in each column does not differ significantly from each other at $p \leq 0.05$, according to the Least Significant Difference (LSD) method

Figure 2(a) shows the acid buffering capacities trend for refined OPF fibres at different steam pressures. The results indicated that OPF fibres refined at 2 and 4 bar did not show any significant differences, as the amount of HCl only required 7 mL to reach a pH of 3. Conversely, the amount of HCl became higher as the steam pressure increased to 6 bar (9 mL), but it continued decreasing to 6 mL at 8 bar of steam pressure. In TMP refining, when the steam pressure and temperature increases above 150-180 °C, the components in the lignocellulosic biomass start to solubilise, where the hemicelluloses would begin to solubilise, followed shortly by the lignin, resulting in a various range of pH of the refined fibre [44]. The hemicellulose degradation results in soluble acidic chemicals such as formic and acetic acids [45], thus making the fibre more acidic. The fibres refined at higher steam pressures are more resistant to acid, thus having a greater acid buffering capacity.

The alkaline buffering capacities for refined OPF fibres are shown in Figure 2(b). The trend shows that the amount of NaOH required to reach a pH of 11 increased significantly from 2 to 8 bar, but little significant differences were observed at 4 and 6 bar of steam pressure. At 8 bar, the alkaline buffering capacity of OPF fibres increased significantly. According to Roffael *et al.,* [46], pulping and refining induce different chemical changes, leading to the formation of different water-soluble compounds such as mono and oligosaccharides, and monobasic acids like formic and acetic acids. Moreover, simple reactive compounds like formaldehyde and furfural are also formed. The higher the temperature, the more soluble compounds are formed. This study suggests that the presence of water-soluble compounds decreases their pH value and increases their alkaline buffering capacity.



(a) (b)

Fig. 2. Buffering capacities of refined OPF fibres in (a) acidic and (b) alkaline conditions

The information on pH and buffering capacity of refined fibre is important when bonding the fibres with bonding agents or adhesives such as Urea Formaldehyde (UF) or Phenol Formaldehyde (PF) in manufacturing MDF. Many researchers [40-47-48] found that fibres pH and buffering capacity significantly affect the curing of adhesives by reducing the gel time when blended with acidic fibres. In addition, the amount of hardener can be adjusted by knowing the pH and buffering capacity trend of refined fibres in order to achieve tolerable curing conditions during the fibre-adhesive mixing process prior to pressing. Because of the presence of OPF fibres in non-wood materials and their higher cellulose content [49], this preliminary study is useful to assess the pH and buffering capacity of OPF fibres by adjusting the steam pressure during the TMP process to obtain appropriate fibre acidity and achieve excellent fibre-adhesive bonding.

The main values of OPF fibre morphology after the refining process are shown in Table 4. Generally, the fibre length reduced with the increase in steam pressure and temperature, but the reduction in fibre length was not significant at bar 2 and 4, and 130 °C and 150 °C of steam pressure and temperature, respectively. The reduction was significant when the temperature was at 170 °C and above. The same pattern was found in fibre width, where the width reduced with the increase in steam pressure and temperature. However, the aspect ratio also decreased with the increase in refining conditions. Among the properties studied were fibre length and width at high and severe conditions; the latter was seemingly more affected.

Table 4
Fibre morphology of refined oil palm frond (OPF) fibres

Refining Conditions	Steam Pressure (bar)	Steam Temperature (°C)	Fibre Length (mm)	Fibre Width (mm)	Fibre Aspect Ratio
Low	2	130	2.77 ^{a}	0.091 ^{a}	30.2^{b}
Medium	4	150	2.65 ^{a}	0.084 ^{a}	31.4^{b}
High	6	170	2.24 ^{b}	0.065 ^{b}	34.6^{a}
Severe	8	190	1.37 ^{c}	0.043 ^{c}	32.1^{b}

Note: The means figured followed by the same letters in each column does not differ significantly from each other at $p \leq 0.05$, according to the Least Significant Difference (LSD) method

The fibre length and width reduction are correlated with the softening effect during the process of TMP. The effect on fibres, which resulted in an easier initial separation and fibrillation, was better at a higher pressure and temperature [50-51]. Numerous researchers have also proposed that steam pressure and temperature are significant parameters in fibre separation, and the development of fibres increased when the pressure and temperature increased, reducing the fibre length [37-52]. The development of the fibres in refining, according to Karniset *et al.,* [53], occurs through the unravelling and peeling of the external fibre layer, and the refining process includes cutting these fibres. The development starts with an initial disintegration of the chips to shives, followed by the disintegration and peeling of the fibre. Furthermore, the plate gap decreases with the increase of steam pressure, resulting in greater grinding and fibrillation force, which further reduces the fibre length [54].

The average fibre aspect ratio in various refining conditions is also shown in Table 3. The fibre length to width ratio is the aspect ratio. Long and thin fibres are considered fibres with a high aspect ratio while being shorter in length and broader in a transverse direction signifies a fibre with a low aspect ratio. The effect of steam pressure in relation to the fibre side was more prominent at steam pressures above 4 bar, as seen in the same table. The aspect ratio of fibres, when refined at 170 °C and higher, was 34.6, but with increasing digestion pressure, the aspect ratio dropped, as the latter suggested. These similar findings were obtained by a study conducted by Nayeri *et al.,* [39], which mentioned that the length of kenaf core fibres decreased significantly with the increase in pulping pressure and time, indicating severe refining conditions.

Scanning electron micrographs (SEM) of fibres refined at several refining conditions (low, medium, high, severe) are shown in Figure 3. Fibre refined at low steam pressure showed incomplete separation, splitting, and delamination (Figures 3(a) and 3(b)). It is believed that at 6 bar, the temperature of 170 °C was insufficient to soften the lignin. Thus, the plasticization of middle lamella may be sufficient to generate well-separated fibres. When the fibres have been sufficiently softened and weakened by steaming during the TMP process, they are separated from the bundles at one end of the fibre [55]. In this case, the fibres were observed to be intact with a slight detachment. In addition, Wan Rosli *et al.,* [49] and Abdul Khalil *et al.,* [56] found that OPF fibre has a much thicker wall than those of other lignocellulosic materials of various sizes of vascular bundles, thus making it higher in rigidity. Figure 3(c) shows that at high pressure, i.e., 6 bar, the surface had been peeled and flaked off, suggesting defibration occurred in the primary wall, exposing another layer. The fibre had a rather smooth and lightly granulated surface, believed to be the waxy substance covering the OPF fibre. However, less granulated material was found on the fibre surface at severe refining conditions, as shown in Figure 3(d).

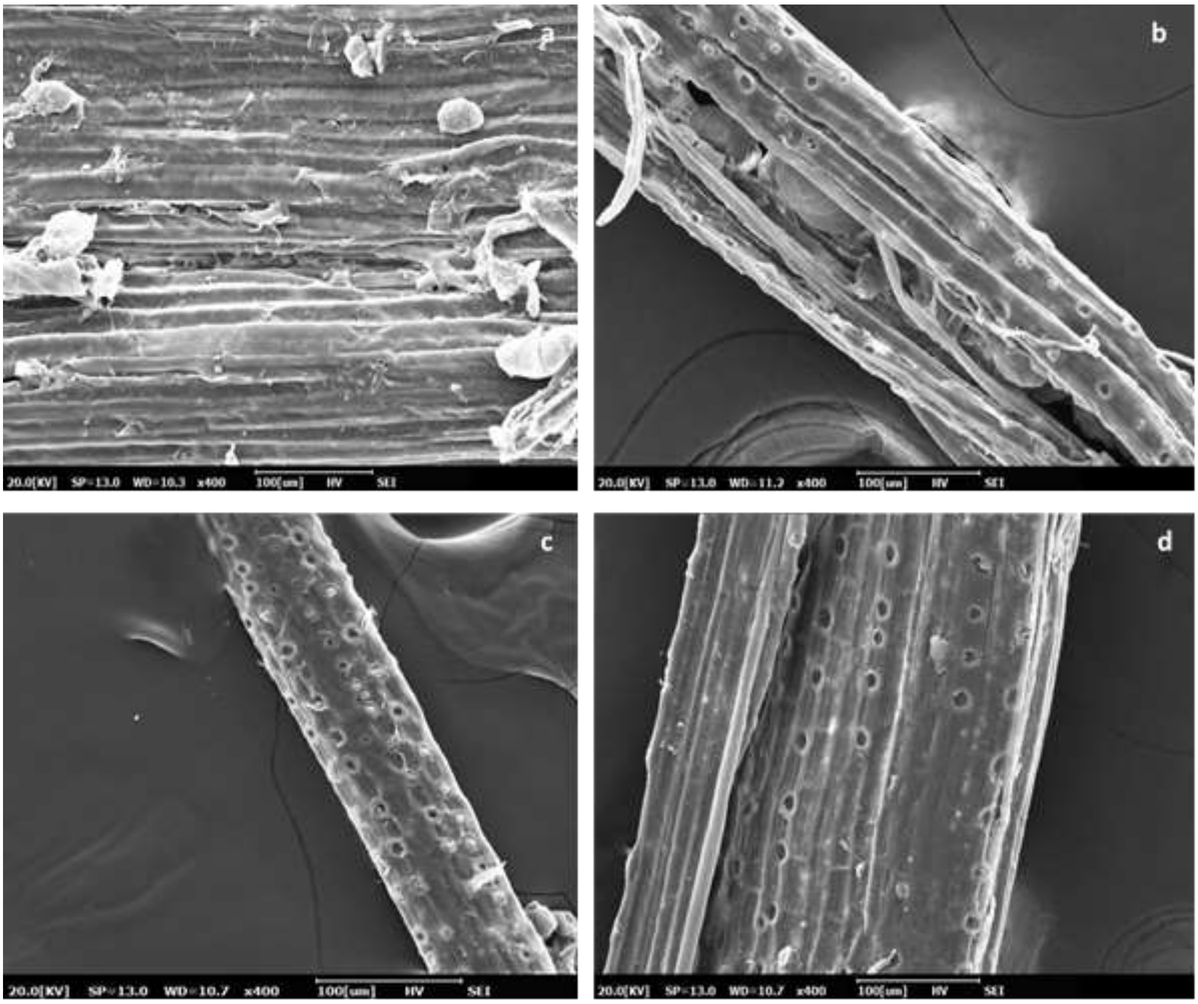


Fig. 3. SEM micrograph of OPF fibre refined at (a) 2 bar and 130 °C, (b) 4 bar and 150 °C, (c) 6 bar and 170 °C, and (d) 8 bar and 190 °C

3.2 Physical and Mechanical Properties of MDF Panels

The mean values of thickness swelling (TS) of the board properties were affected by different refining conditions, as shown in Figure 4. The TS was significantly different when OPF fibre was refined at least at medium refining conditions (4 bar and 150 °C). For instance, at a high refining condition, the increase of steam pressure from 4 to 6 bar and steam temperature from 150 to 170 °C had resulted in an improvement in TS from 15.17% to 13.88%. At higher temperatures, the heat would be sufficiently high to soften the lignin at the middle lamella. It was found that when the steam pressure is increased to 8 bar, the TS value will be increased from 13.88 to 14.07%. The lowest TS value of 13.88% was found for panels made using a steam pressure of 6 bar and steam temperature of 170 °C.

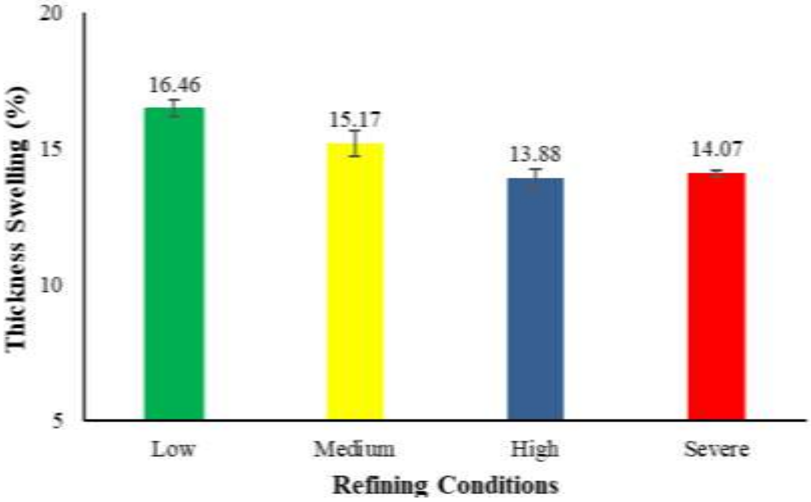


Fig. 4. Thickness swelling values of the samples manufactured from OPF fibres at different refining conditions

This can be explained by longer fibres that have relatively higher board strength. Refined fibre at 5 bar of digestion pressure and 5 minutes of heating time produced the longest fibre (Table 4). This resulted in better dimensional stability of panels. Such findings are supported by Maloney [57], who showed that fibre length strongly affects the dimensional stability of fibreboards. The reduction in TS is associated with a higher amount of short fibres (Table 3) that absorb less water intake [38]. Halvarsson *et al.,* [41] explained that short fibres created more fibre-to-fibre network during mat formatting, thus creating a better cross arrangement and interlocking structure between fibres and consequently improving the dimensional stability panels. In addition, Halvarsson [41] also explained that reducing the amorphous region in the cellulose structure occurs when lignocellulosic materials are exposed to heat. The -OH groups in the cellulose and hydrophobic components are removed, producing a more stable board. However, an opposite observation was seen in the TS value of the panel at the severe refining condition (8 bar and 190 °C). This might be due to the excessive amount of fibre that disrupts the bonding between resinated fibres.

For panels made from OPF fibres, the Internal Bonding (IB) values increased with increased steam pressure from 2 to 4 and 6 bar, as shown in Figure 5. This phenomenon can be related to the shorter fibre length produced from high and severe refining conditions. Short fibres increase the bonding area covered by the UF resin, generating an enhanced bonding between fibres during the pressing process and improving bonding [58]. Moreover, severe refining conditions produced more short and fine fibres, creating insufficient resin for all fibres in the mat-forming. Other than that, it was observed that IB was strongly related to the pH value of fibres. The value of IB strength increased at the low pH value of fibres. The refining process of OPF fibres at the severe refining condition resulted in acidic fibres forming, hence, introducing a problem during fibre blending and mat pressing processes. These acidic fibres required less time to form a mat during mat-forming. Consequently, most of the resin had pre-cured prior to actual hot pressing and created a poor distribution of resin and fibres.

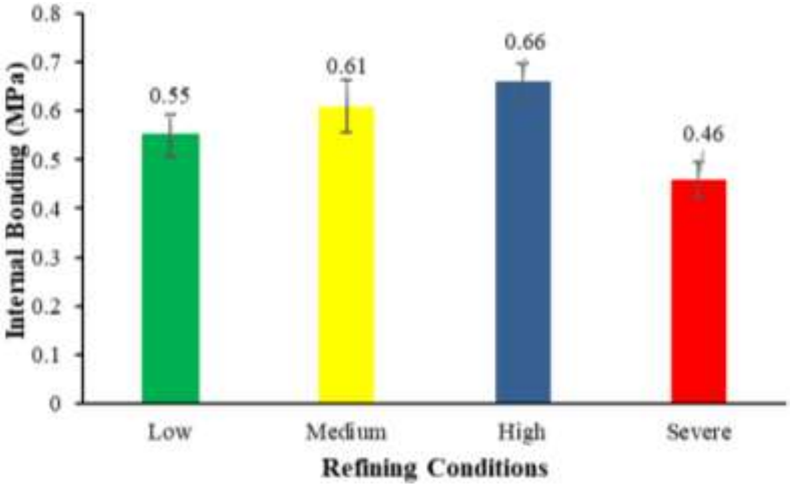
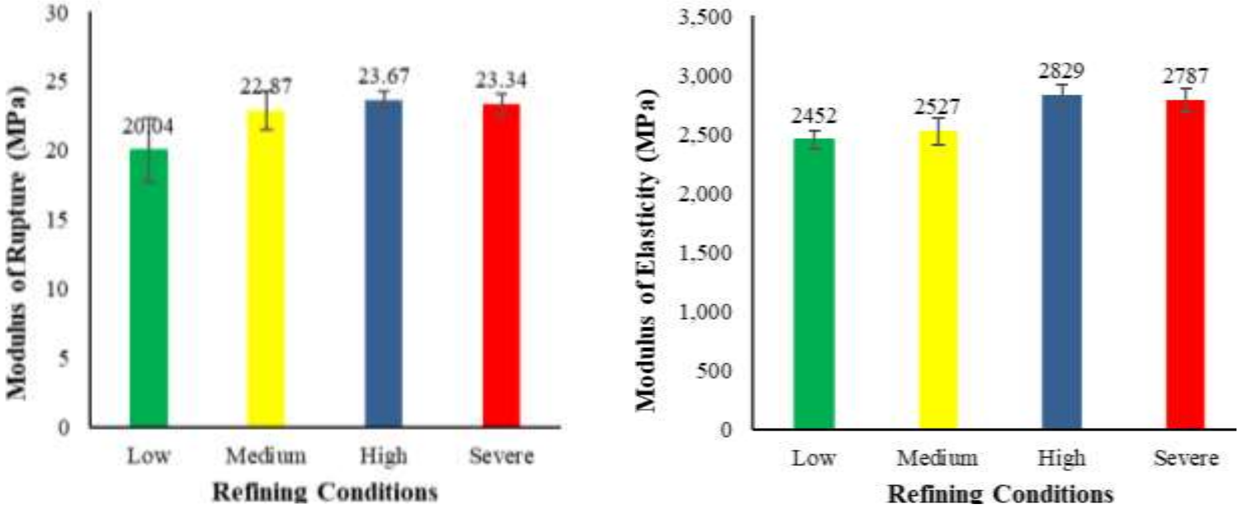


Fig. 5. Internal bonding of the samples manufactured from OPF fibres at different refining conditions

As displayed in Figures 6(a) and 6(b), the samples' MOR and MOE increased with increasing steam pressure and temperature. The panel refined at the high refining condition (6 bar and 170 °C) gave the highest MOR and MOE values despite having shorter fibre length and small fibre width but higher in aspect ratio. Several plausible explanations can be made for this phenomenon. It was found that fibre was separated when produced at high and severe refining conditions, thus making the flow of the resin more efficient between fibres.



(a) (b)

Fig. 6. (a) Modulus of rupture (MOR) and (b) modulus of elasticity (MOE) of the samples manufactured from OPF fibres with different refining conditions

Furthermore, the availability of short fibres consequently makes the mat easily compressed. This gives better compaction and results in higher bending strength. It was found that thin fibres are more effective in load transfer than thick fibres [59]. However, continued steam pressure and temperature up to 8 bar and 190 °C had mixed effects on the bending properties. Almost all MOR and MOE of the samples improved slightly as the steam pressure and temperature increased but slightly dropped when the refining condition became severe. It seems that a higher degree of hydrolysis occurred at high steam pressure and temperature, creating a reduction in the fibre strength [60].

4. Conclusion

This study showed that fibre from different refining parameters produced different properties of the refined fibre. Refining at higher pressure produced fibre with greater acid buffering capacity than refining at low steam pressure; thus, it is more sensitive to acid. Medium to high refining conditions produced acceptable fibre length and fibre widths, which resulted in better bonding, bending strength of the panels, and lower TS properties of the sample. While, severe refining conditions produced shorter and more fine fibres, with low aspect IB, bending, and physical properties. It was found that the refining condition was crucial parameters that need to be considered to have better properties of MDF. The panel refined at a steam pressure of 6 bar and a steam temperature of 170 °C well performed in TS, IB, MOR, and MOE.

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