Chemical-free Thermomechanical Pulping of Empty Fruit Bunch and Sugarcane Bagasse

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The biomass resources oil palm empty fruit bunch (EFB) and sugarcane bagasse, which are residues from the palm oil and sugar industries, continue to be investigated for more applications. With increasing concern for the environment, cleaner production has been a worldwide aim of researchers. In this study, thermomechanical pulp (TMP) from EFB and sugarcane bagasse was prepared with disc refining after steam pretreatment of the raw materials. Afterwards, refining and handsheet properties of TMP using various percentages of unbleached soda bagasse pulp (USBP) were studied. Fiber characterizations and handsheet properties showed that pulp of acceptable quality was obtained *via* thermomechanical pulping. Moreover, energy consumption during PFI refining of EFB TMP was higher than that of bagasse TMP. Physical properties were further enhanced through introduction of USBP. The results firmly support the feasibility of cleaner thermomechanical pulping of EFB and sugarcane bagasse.

Keywords: Empty fruit bunch; Sugarcane bagasse; Thermomechanical pulp; PFI refining

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INTRODUCTION

The awareness of negative environmental impact has indirectly contributed to the revolution of the pulp and paper industry. While trying to maintain the strength of paper and paperboard products (Hubbe 2014), the pulp and paper industry has been seeking for new raw material to take the place of wood at the same time (Marín *et al.* 2009; Sharma *et al.* 2011; Ferhi *et al.* 2014; Ooi *et al.* 2017; Emmclan *et al.* 2018). Non-wood raw materials, such as bamboo, wheat straw, and sugarcane (*Saccharum officinarum*) bagasse, have already been utilized in practical production in China, *e.g.*, the sugar industry in South China, where sugarcane bagasse has already been used as raw material for pulping and papermaking. The palm oil industry in South East Asia annually produces enormous biomass resources such as empty fruit bunch, palm kernel shell, oil palm trunk, *etc.* (Ooi *et al.* 2017). Among these biomass resources, empty fruit bunch (EFB) is an abundantly available fibrous residue left after the separation of palm fruits (Singh *et al.* 2013). It is wasteful if EFB is simply buried or combusted.

The application of sugarcane bagasse as a feedstock for soda pulping has reached a mature stage. As for EFB, various methods, such as soda-anthraquinone pulping, semi-chemical pulping, thermomechanical pulping, organic solvent pulping, and bio-pulping, have been investigated (Rodríguez *et al.* 2008; Jiménez *et al.* 2009; Risdianto and Sugesty 2015; Mulyantara *et al.* 2017). The studies mentioned above used chemicals that can give rise to environmental problems if not seriously treated.

Despite many studies that have reported on various pulping methods, there is still a lack of more environmentally friendly and less expensive methods for EFB application. Pulping by a mechanical method could maximize the yield with low production cost while maintaining the small impact on the environment. Mechanical pulping does have some advantages. The high bulk and stiffness of mechanical pulp are desirable in paperboard production (Liu *et al.* 2012). Additionally, the opacity of mechanical pulp is favorable in obtaining good printing products (Zhang *et al.* 2011). However, such advantages are achieved with compromised pulp quality. Normally, mechanical pulp, especially without chemical treatment, is used as a partial substitution of chemical pulp for papermaking. Because the fiber bond of mechanical pulp is not as strong as chemical pulp, the application of mechanical pulp is hindered by the low physical strength of the resulting paper (Zhang *et al*. 2011).

Therefore, one of the major research targets of all time is to enhance the pulp quality for higher value applications. Various methods, such as mild chemical pretreatment, steam treatment, enzymatic pretreatment, and biological pretreatment, have been utilized in the improvement of mechanical pulping (Ferraz *et al.* 2008; Ahmadi *et al.* 2010; Lei *et al.* 2012; Mulyantara *et al.* 2017). Among these solutions, steam pretreatment stands out as having the slightest influence on the environment and low manufacturing cost. The typical steam preheating temperature for wood chips before mechanical pulping is 120 to 130 °C, accompanied with chemical treatment. The major applications of thermomechanical pulp (TMP) produced with steam pretreatment are used for making corrugating medium and packaging paper or paperboard, because of the high stiffness. Furthermore, TMP can be used in printing paper, coated paper, and some other applications.

To enrich the raw material selections with a cleaner production method, chemical-free thermomechanical pulping was performed with EFB and sugarcane bagasse. The objectives were to explore thermomechanical pulping with EFB and sugarcane bagasse as raw materials, without using any other chemicals, and to evaluate their mechanical properties. Furthermore, various amounts of chemical pulp were added to mechanical pulp to investigate the refining and papermaking behavior of pulp mixtures.

EXPERIMENTAL

Materials

The EFB was obtained from Heng Huat Group (Pulau Pinang, Malaysia). Sugarcane bagasse (without depithing) and unbleached alkaline bagasse pulp (USBP) were provided by Guangxi Boguan Environmental Products Co., Ltd. (Guangxi, China). The primitive form of the raw EFB was fiber strands several centimeters in length (> 10 cm) and diameter less than 1 mm (Fig. 1). Sugarcane bagasse was in the form of stubby fiber strands shorter than EFB and sometimes thicker than several millimeters (Fig. 1). The moisture content of USBP was measured after full disintegration. The chemical components of EFB raw material were analyzed following the determination of structural carbohydrates and lignin using NREL laboratory analytical procedures for standard biomass (Sluiter *et al.* 2008). The extractives content in organic solvents was measured according to TAPPI T204 cm-97 (1997) and ash as per TAPPI T211 om-93 (1993).

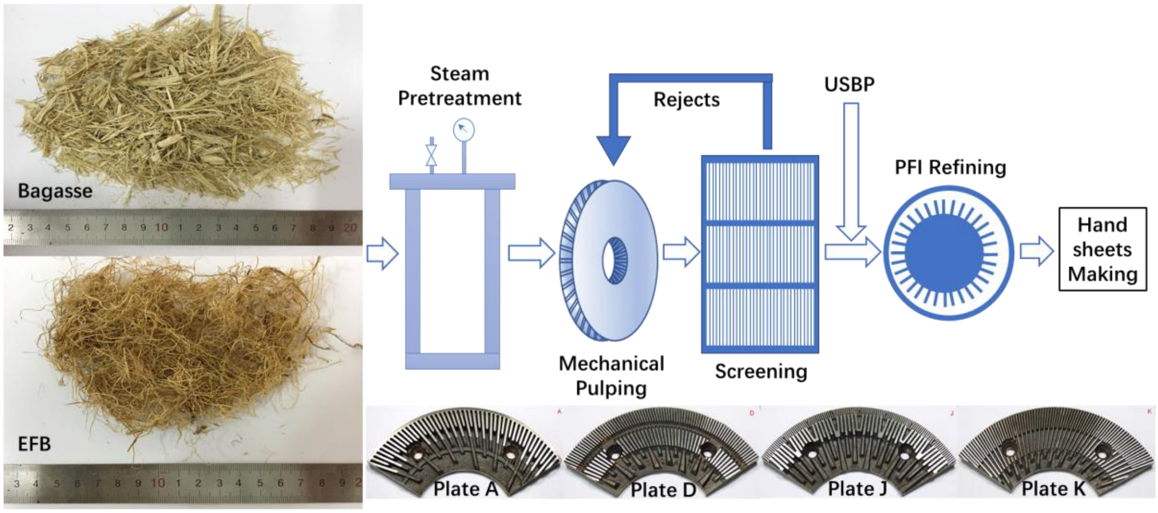


Fig. 1. Schematic process used for the preparation of thermomechanical pulp in this study

Methods

Preparation of thermomechanical pulp

Before steam pretreatment, water was sprayed onto EFB and bagasse materials to remove any mud and dust. Then, the wet raw material was placed in a vertical digester (10-L). The steam pretreatment was completed at 0.6 MPa pressure at 160 °C (±2 °C) for approximately 45 min. At this temperature, lignin and hemicellulose were found to be slightly removed during steam pretreatment (Luo *et al*. 2014), which could be beneficial to mechanical pulping. When the steam pretreatment was finished, the hot (60 to 70 °C) material was subjected to a mechanical pulping process under atmosphere pressure and room temperature with a continuous high-consistency disc refiner (2500-II; Kumagai Riki Kogyo Co., Ltd., Tokyo, Japan) at high consistency (20% to 25%) and disc clearance of 0.6 mm. Plate D was directly used for mechanical pulping. The plate D was selected in consideration of the relatively small particle size of EFB and bagasse (compared with wood chips), which didn't require a lot of breaking effect. Compared with other plates whose function is more focused on either breaking or refining, plate D does have some breaking effect, while coarse and refining zones account for the two thirds area of plate D, as shown in Fig. 1. The gap between two refining discs was set at 0.6 mm because it was a critical point where steady pulping process between strong shear and friction effect was balanced. Afterwards, the stock from the first stage was screened with a 0.2-mm diaphragm screen. Rejects were refined and screened at the same condition as the first stage. The accepts from the first stage and second stage were combined and stored as the pulp for refining and used for making handsheets. In addition, yield and drainability were measured for the evaluation of the pulping process. Fiber quality analysis was completed with a fiber analyzer (MORFI, Compact Techpap, Saint Martin d'Hères, France). Fiber macrostructure was studied with a light microscope (DMi8 C; Leica, Wetzlar, Germany).

Pulp refining and handsheets making

Mixtures with different formulations of USBP and TMP were prepared for PFI refining as per ISO 5264-2 (2002). Various formulations were refined to Canadian Standard Freeness (CSF) 320 (± 20) mL for handsheet preparation and microscopic analysis. In addition, the handsheets were produced in accordance with standard ISO 5269-2 (2004).

Handsheets properties measurement

Basic paper properties of basis weight, thickness, bulk, density, and brightness were measured. The physical properties were also measured, such as tensile strength as per ISO 1924-2 (2008), bursting strength as per ISO 2758 (2014), tearing strength as per ISO 1974 (2012), and ring crush test (RCT) as per ISO 12192 (2011). Indexes of those properties were calculated to avoid the errors brought by basis weight difference.

RESULTS AND DISCUSSION

Chemical Composition of EFB and Bagasse

To estimate the value for pulping and papermaking, the chemical composition of raw material was analyzed first. EFB contains cellulose (44.9%), holocellulose (67.6%), lignin (22.5%), organic solvents extractives (4.3%), and ash (1.5%), which is similar to the chemical compositions of sugarcane bagasse after depithing (Zhao *et al.* 2011). In addition, EFB has higher cellulose content and lower organic solvent extractives content, compared with wheat straw which has 34.9% cellulose, 7.6% organic solvents extractives and 7.6% ash (Tozluoğlu *et al.* 2015). This confirms the potential of EFB being used as feedstock for pulping and papermaking.

Yield

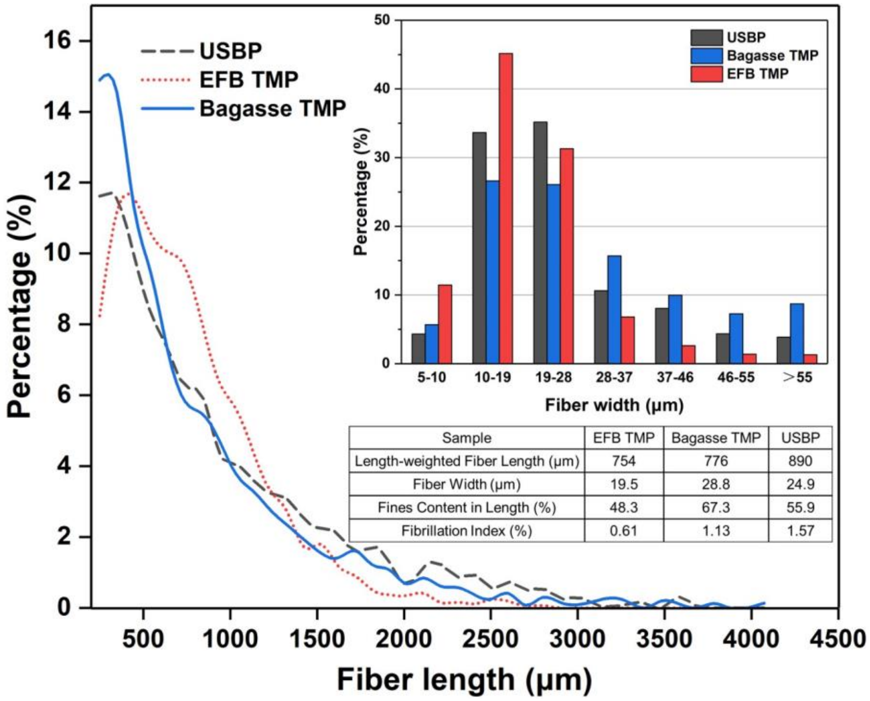
Yield results are shown in Table 1. The total yield for both EFB and bagasse raw material in the first stage was approximately 80%. The major loss in the yield could have been due to the non-fiber content and some fibers that were refined into small particles that could pass through 200-mesh filtration fabric. The screened yield of the first stage for EFB (67.7%) was almost twice as that of sugarcane bagasse (35.5%). This difference was related to the primitive form of the raw material. The EFB material consisted of long thin fiber strands. By contrast, sugarcane bagasse contained stubby fiber strands and first needed to be ground into smaller particles, resulting in a high total yield (77.2%) but low-screened yield (60.4%). There remained not enough rejects of EFB TMP and bagasse TMP in the second stage for another stage of mechanical pulping.

Table 1. Pulp Yield During Mechanical Pulping Process

Sample	First Stage		Second Stage	
	Total Yield (%)	Screened Yield (%)	Final Total Yield (%)	Final Screened Yield (%)
EFB TMP	82.9	67.7	79.9	77.7
Bagasse TMP	86.2	35.5	77.2	60.4

Fiber Characterization of EFB TMP, Bagasse TMP, and USBP

Fiber morphology has a vital influence on the papermaking process and hence the physical properties of paper sheets formed. A summary of the length and width distributions of TMP fibers obtained is shown in Fig. 2. The length-weighted fiber length of EFB TMP was 754 μm and bagasse TMP was 776 μm, which belonged to the category of short fibers. Differently, the length of bagasse TMP fibers was mainly within the 0 to 500 μm region. As for width, there existed a notable difference between the two kinds of TMP. The average width of EFB TMP fibers was 20 μm, whereas bagasse TMP was 29 μm. However, the width distribution of bagasse TMP fibers was more scattered. This scattered width distribution of bagasse TMP came from the uniformity in raw material morphology and mild breaking effect of the refining disc used. The fiber length distribution of USBP was more weighted in long fiber length, while that of USBP fibers were thicker than EFB TMP fibers.



Sample	EFB TMP	Bagasse TMP	USBP
Length-weighted Fiber Length (μm)	754	776	890
Fiber Width (μm)	19.5	28.8	24.9
Fines Content in Length (%)	48.3	67.3	55.9
Fibrillation Index (%)	0.61	1.13	1.57

Fig. 2. Fiber length and width distributions of EFB TMP, Bagasse TMP, and USBP

Another thing worth mentioning is that the fines content (in length) of EFB TMP and bagasse TMP were 48.3% and 67.3%, respectively. High fines content and thicker fiber width indicated that a lot of sugarcane bagasse fibers were cut into small pieces during mechanical pulping process. The pith in sugarcane bagasse also played a part in the fines content. In contrast, the individual fibers in fiber strands of EFB were well separated during mechanical pulping process. Figure 4 shows that a lot of cell fragments could be observed in bagasse TMP and USBP, and EFB TMP fiber appeared slender. The high aspect ratio and comparatively low fines content of EFB TMP revealed that ideal mechanical pulp fiber could be fabricated with this simpler pulping process.

Pulp Behaviors During PFI Refining

The pulp refining process is necessary to enhance fiber bonding properties (Gharehkhani *et al.* 2015). The main aim in refining is to make the fiber fibrillate, and thus improve the bonding between fibers in a paper sheet (Zukeri *et al.* 2012). However, refining the mechanical pulp alone could be a high-cost process with little fibrillation. To balance energy consumption and to study the physical properties of the two thermomechanically obtained pulp, various percentages of USBP were mixed in the TMP for PFI refining and handsheets making.

Energy consumption in the PFI refining process is shown in Fig. 3. With USBP fraction growth in the EFB TMP pulp mixture, the energy required to refine the pulps to 320 mL CSF was decreased. For example, the energy consumption dropped to 37.7 kW•h from 68.2 kW•h with the addition of 40% USBP. As lignin plays the role of an adhesive that sticks the macro fibers together to maintain the fiber form (Li *et al.* 2016), the high content of lignin in the pulp fibers, without softening treatment, would prevent the fibrillation and swelling, thus introducing more difficulties to the refining process (Eriksson *et al.* 1991). Consequently, more EFB TMP in the pulp resulted in more energy that was required.

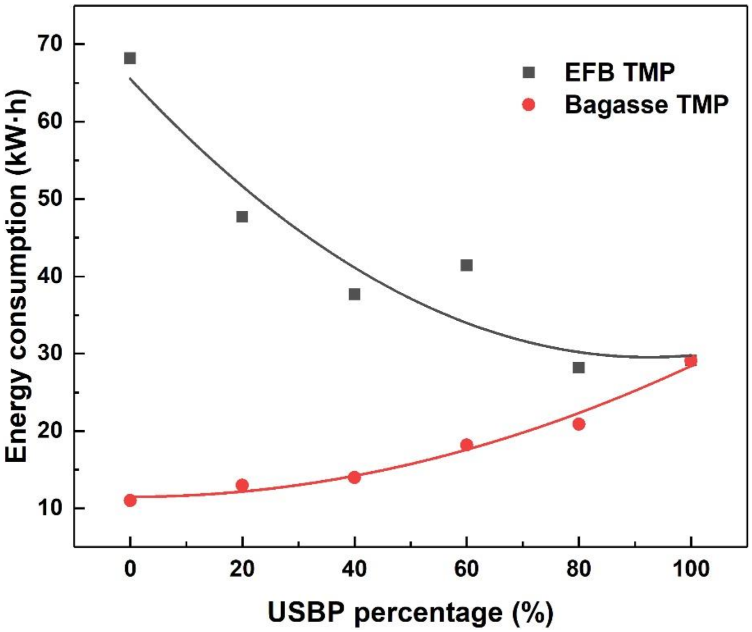


Fig. 3. The difference in refining process between EFB TMP and bagasse TMP

Initial CSF variations of different pulp formulations cannot be neglected. The figures in Table 2 show the CSF changes in PFI refining. Compared to USBP fibers, the EFB TMP fibers were slightly shorter and richer in lignin content, making the fibers stiff and inflexible, which accounts for the high initial CSF of EFB TMP (610 mL). However, the initial CSF of EFB TMP in this work is lower than that of soda-anthraquinone pulp (CSF 710 mL, 15 °SR) (Jiménez *et al*. 2009). This could have been explained by the high fines content brought by mechanical pulping. In contrast, the USBP pulp (initial CSF 485 mL) fibers were longer and more flexible, and the CSF of the pulp mixture decreased when USBP was introduced.

Table 2. Initial and Final CSF of Pulp Mixtures During PFI Refining

USBP Percentage (%)	EFB TMP		Bagasse TMP	
	Initial CSF (mL)	Final CSF (mL)	Initial CSF (mL)	Final CSF (mL)
0	610	305	495	295
20	570	310	490	285
40	560	305	535	290
60	560	310	530	305
80	535	285	555	319
100	485	310	485	310

Nevertheless, things were quite different with bagasse TMP. Although the pulping procedure was the same, the energy consumption in the refining process of the mixture of bagasse TMP and USBP increased a little with increased USBP content (Fig. 3). The initial CSF of bagasse TMP (495 mL, Table 2) was quite low, such that it almost reached the USBP level (485 mL), while the initial CSF of pulp mixtures somehow increased a little (*e.g.*, 535 mL for 40% USBP and 530 mL for 60% USBP). The fines content in bagasse TMP was much higher than that in EFB TMP. In addition, bagasse TMP responded to refining so sensitively that the fines content jumped up to 82.4% from 67.3% of the unrefined bagasse TMP (Table 3). Therefore, the CSF of bagasse TMP showed a swifter decrease than USBP did during refining; this could be the reason for the increase in energy consumption with the growth of USBP.

Other than energy consumption, the results from fiber analysis of EFB TMP, bagasse TMP, and USBP after PFI refining is summarized in Table 3. A minimal decrease in fiber length and apparent increase in fines content was observed in all three types of pulp after PFI refining. However, the fibers in bagasse TMP were better preserved than the other two. The fibrillation index rose by a varying degree: 1.31% for EFB TMP, 1.13% for bagasse TMP, and 0.05% for USBP. The individual fiber views after PFI refining are shown in Fig. 4. The fibers of EFB TMP and bagasse TMP basically remained the same after mild PFI refining process. However, a common change that could be observed was the increased non-fiber and fines content (cell fragment).

Table 3. Fiber Analysis Summary After PFI Refining

Sample	EFB TMP	Bagasse TMP	USBP
Length-weighted Fiber Length (μm)	691	744	850
Fiber Width (μm)	19.7	28.4	24.1
Fines Content in Length (%)	72.1	82.4	60.0
Fibrillation Index (%)	1.92	2.26	1.62

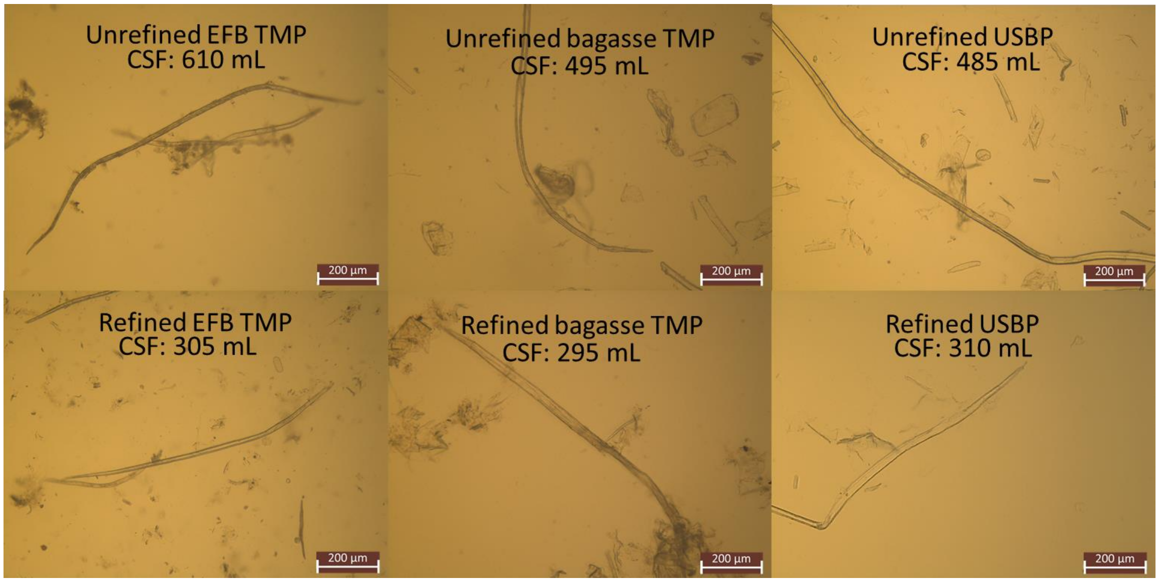


Fig. 4. Microscopic image of fibers

In summary, the major effects of the PFI refining process on EFB TMP and bagasse TMP were fiber shortening, fines formation, and a little fibrillation. The energy consumption of EFB TMP was higher than that of bagasse TMP. However, with the introduction of USBP into EFB TMP, the energy consumption in the refining was brought down to an acceptable level. Though the fibrillation was not that desirable for TMP, the refining process is still inevitable in obtaining good mechanical properties of the paper sheet. A specific refining strategy should be made combining the practical application requirements and pulp behaviors in the refining process.

Handsheets' Properties

The basic parameters, such as basis weight and density, are of great importance in studying the mechanical properties of handsheets. The basis weight of handsheets was kept around 100 g/m^2 and the density at 0.5 g/cm^3 to make sure that the study of the following mechanical properties were more precise and better (Table 4).

Table 4. Basic Parameters of Handsheets

USBP Percentage (%)	EFB TMP		Bagasse TMP	
	Basis Weight (g/m^2)	Density (g/cm^3)	Basis Weight (g/m^2)	Density (g/cm^3)
0	101	0.63	97	0.44
20	105	0.46	101	0.47
40	104	0.47	102	0.50
60	107	0.51	101	0.54
80	103	0.54	107	0.60
100	109	0.45	109	0.45

Due to the fiber content variance, there was an obvious difference between the handsheets structures of EFB TMP and bagasse TMP. The major distinction was observed in the air permeance (Fig. 5).

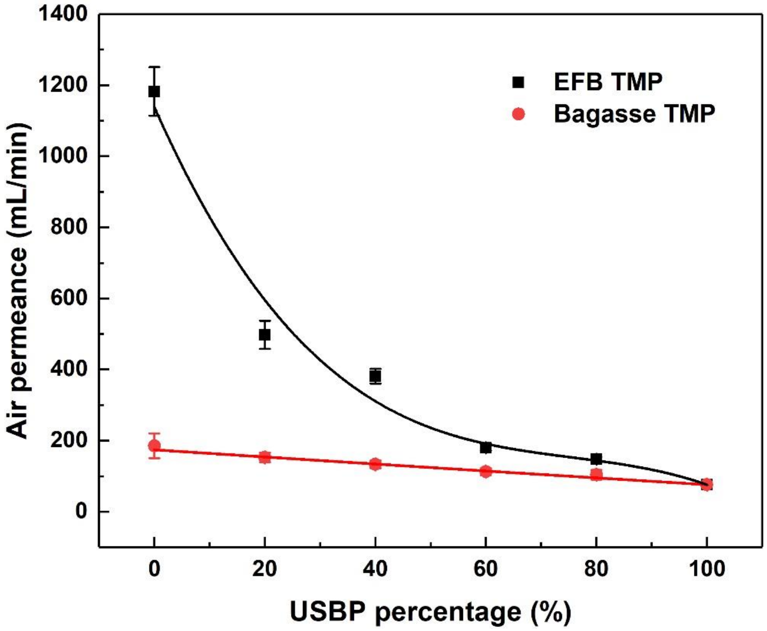


Fig. 5. Air permeance variation with different USBP percentages

The air permeance of EFB TMP decreased noticeably with the introduction of USBP. After the USBP percentage reached 60%, the air permeance dropped more slowly than before. However, air permeance of bagasse TMP handsheets was far lower than that of EFB TMP handsheets. Provided that there was not much difference in density, the high fines content was the reason for the low air permeance of bagasse TMP handsheets. It is widely acknowledged that the fines content of pulp reduces the drainability (Seth 1990a), and the existence of fines fills the empty space in the fiber network, which blocks the air flow and improves the smoothness (Joseleau *et al*. 2012). Additionally, the high air permeance of EFB TMP handsheets suggested that the fiber network was relatively loose and porous.

Tensile strength is one of the most commonly reported physical properties. The curves in Fig. 6a exhibit how the tensile strength index changed with various USBP percentages. Apparent improvement was observed in both EFB TMP and bagasse TMP. With 60% USBP in TMP, the tensile strength index reached 38.1 N•m/g for EFB TMP handsheets and 32.9 N•m/g for bagasse TMP handsheets, while the original tensile strength index for EFB TMP and bagasse TMP handsheets were 23.9 N•m/g and 22.0 N•m/g, respectively, even higher than mild NaOH-treated TMP handsheets (Harsono *et al.* 2015).

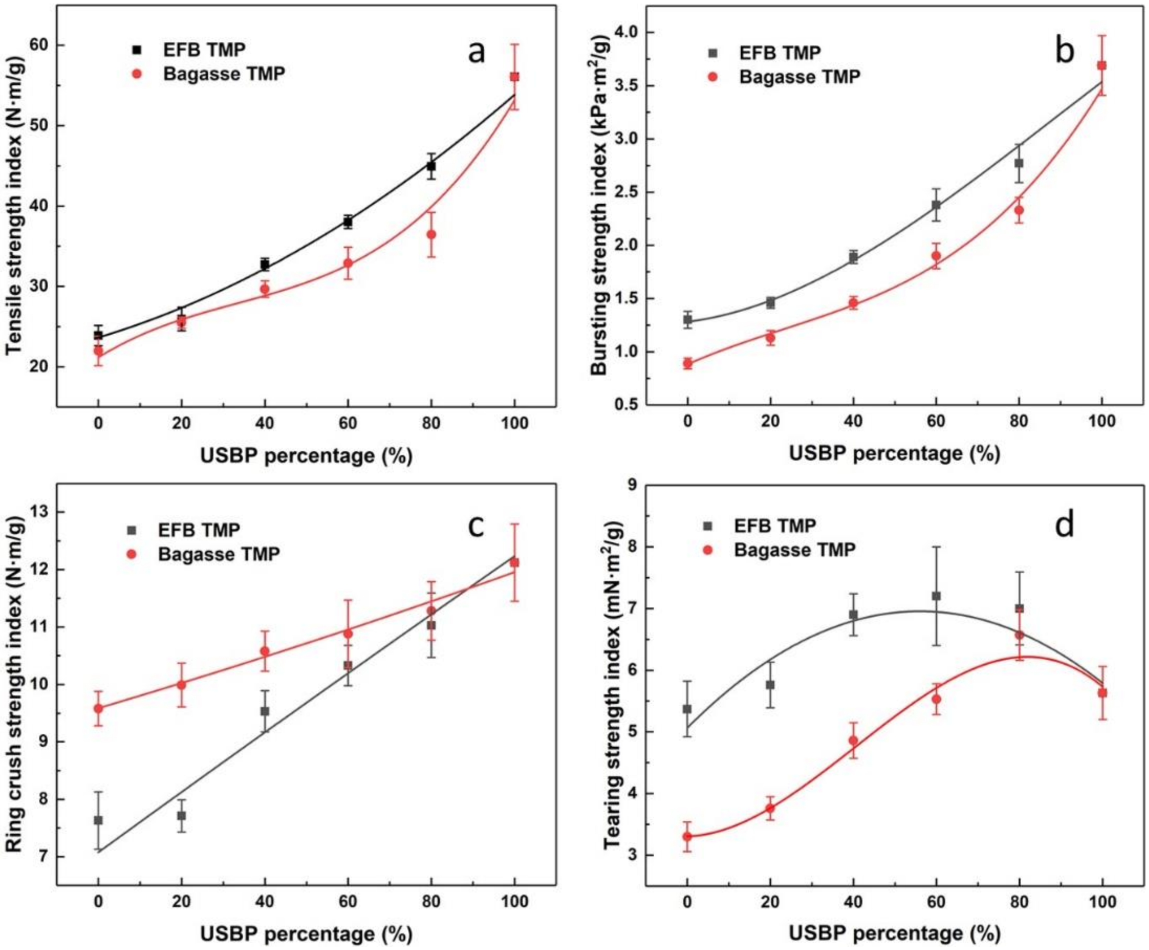


Fig. 6. Influence of USBP on physical strength of handsheets: a) Tensile strength index variation; b) Bursting strength index variation; c) RCT index variation; and d) Tearing strength index variation

The loose and porous structure of EFB TMP handsheets, demonstrated by high air permeance (Fig. 5), have revealed that the fiber bonding was not strong enough. If fiber bonding is weak, any enhancement in fiber bonding could lead to improvement of tensile strength (Larsson *et al.* 2018). After the pulp was mixed with USBP, not only was the average length of pulp fibers increased, but also the fiber bonding and physical entanglement was improved, evidenced by the decrease in air permeance (Wang *et al.* 2010). The enhancement in tensile strength came from the joint effect of improved fiber length and fiber bonding (Seth 1990a). Delignified USBP fibers were longer, more flexible, and easier to deform, which was beneficial for the fiber contact and interfiber bonding (Li *et al*. 2016). The variation of bursting strength (Fig. 6b) with various USBP percentages for both mechanical pulp had a lot in common with tensile strength. In general, the EFB TMP had slightly better performance than bagasse TMP. This difference might be attributed to the scattered fiber width distribution of bagasse TMP, which meant bagasse TMP fibers were coarser and fiber bond in the handsheets was weaker (Seth 1990b).

The RCT index variation is shown in Fig. 6c. It was the only physico-mechanical property in which EFB TMP had poorer performance than bagasse TMP. The RCT index of 100% bagasse TMP handsheets was 9.58 N•m/g, whereas in 100% USBP handsheets it was 12.12 N•m/g. In contrast, the increase brought by USBP was considerable for EFB TMP. The curve started from 7.63 N•m/g and stopped at 12.12 N•m/g. The RCT indexes of both TMP exhibited a certain correlation with the USBP percentage.

Much attention is also paid to the tearing strength in the papermaking industry. In Fig. 6d, the tearing strength index of handsheets from both TMP first increased and decreased a little in the end. The tearing strength index of EFB TMP handsheets reached a maximum (7.20 mN•m^2/g) with the 60% USBP content. The turning point for bagasse TMP handsheets came late at approximately 80%, and was a little lower (6.57 mN•m^2/g). The tearing strength index of 100% EFB TMP handsheets (5.37 mN•m^2/g) was quite close to that of 100% USBP (5.63 mN•m^2/g). The addition of USBP improved the fiber bonding in handsheets; therefore the energy needed to pull out the fibers increased (Shao and Li 2006). When fiber bonding kept improving, more fiber broke instead of being pulled out during testing. Therefore, less work was consumed and the tearing strength index showed a minimal decrease (Seth 1990b).

CONCLUSIONS

1. Empty fruit bunch raw material was more fibrillated than bagasse. More breaking effect was needed in the mechanical pulping of bagasse. The length-weighted fiber length of EFB TMP before PFI refining was 754 μm and bagasse was 776 μm. Meanwhile, fines content in EFB TMP was much lower than that of bagasse TMP. More energy was needed in PFI refining of EFB TMP.
2. The structure of handsheets made from EFB TMP was loose and porous but outperformed that prepared bagasse TMP in tensile strength (23.89 N•m/g), bursting strength (1.3 kPa•m^2/g), and tearing strength (5.37 mN•m^2/g).
3. With a small amount of USBP, both TMP products were suitable for corrugating medium or other packaging paper product. Besides, they could be utilized as partial substitution in chemical pulp to reduce production cost.

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