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Recovery of Pulp from Oil Palm Empty Fruit Bunch and Used Paper for Sustainable Paper Production

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Agricultural waste residue such as empty fruit bunch (EFB) has great potential as an alternative feedstock in pulp and paper industry. This study provides insights into the use of EFB as an alternative non-wood fibre resource for pulping and papermaking. EFB was mixed with used paper (UP) according to the ratio of 100:0, 75:25, 50:50, 25:75 on dry basis. The hemi-cellulose and lignin contents in EFB was removed by soda-pulping using 15% w/v sodium hydroxide for 30 minutes at 100°C. Chemical analyses were performed to determine the ash content, lignin content, and the cellulose content (Rowel method). Physical and mechanical properties of the EFB/UP paper were characterised according to the TAPPI Standards including grammage, porosity, moisture content and tensile strength. The average fibre length of all EFB/UP papers showed different fibre length ranging from 1.0 to 1.2 mm. EFB25 (25% EFB) was found to have the least moisture content of 7.28% meanwhile EFB100 had the least ash content of 2.28% and the highest cellulose and lignin content of 45.22% and 26.5%, respectively. EFB25 demonstrated the highest tensile index of 2.01 Nm/g. There are no major colour changes and no trace of fungal growth on the surface of all paper samples after 4 weeks of storage without temperature and humidity control. It was found that paper with EFB25 displayed good physical appearance with grammage of 59.8 g/m^2 that is almost comparable to commercialised paper of 70 g/m^2 and suitable for writing.

Keywords: empty fruit bunch; cellulose; lignin; used paper; pulp; paper production; TAPPI standard

I. INTRODUCTION

Paper is important not only in the education sector, but also in printing businesses and packaging industries. It is reported that the consumption of paper worldwide has increased 400% in the last 26 years. The world consumes around 250 million metric tons of paper in 1992 and the utilisation of paper has risen to more than 400 million metric tons in 2018 (Berg & Lingqvist, 2019). Thus in 2020-2022, the demand for paper has surpassed 500 million metric tons, as global demand for paper is predicted to rise roughly 2.1% annually (Suseno *et al.*, 2017). Cellulose, hemicellulose, and lignin are familiar elements in the pulp and paper industries. The strength of a sheet of paper relies on fibre sources of high cellulose content (>40%) with lignin content lower than 30% (Ververis *et. al.*, 2004; Ramdhonee & Jeetah, 2017).

Wood pulp is the primary fibrous feed material from which the paper is produced. More than half of the wood cut worldwide is used to produce some form of paper products, equivalent to about 65 million tons of roundwood or 36% of the annual timber harvested (Bowyer *et al.*, 2014). The high demand of paper and derivative products on a daily basis is excessively significant and may lead to large scale of illegal logging and deforestation. Nevertheless, pulping technology of either chemical or mechanical would also affect the

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number of trees to be used. Industry specialists suggest that approximately 24 trees are expected to be used to manufacture 1 metric ton of paper in chemical pulping which often stated as Kraft pulping (Kiprop, 2018).

Attributed to the high annual yields of alternative fibre sources from agricultural residues such as straws, sugarcane bagasse, bamboo, different types of leaves and wheat, biomass waste (Khairol Anuar *et al.*, 2021) has drawn attentions from global researchers in pulp and paper production industries (Fahmy *et al.*, 2017). Furthermore, low recycling rate of used paper in certain countries also has increased the development of papermaking from wood fibres which cause forestry destruction. Table 1 shows some potential agricultural wastes that can be utilised as papermaking feedstock including sugarcane bagasse (Hamzeh *et al.*, 2013), bamboo (Pande, 1998; Vena *et al.*, 2013) and banana stem (Ramdhonee & Jeetah, 2017). Producing paper from biomass fibre waste is beneficial since most waste contained less lignin than timber, in addition to the requirement of lower activation energies due to much simpler delignification process (Risdianto, Kardiansyah & Sugiharto, 2016). Thus, such biomass residue is an ideal and viable solution to minimise the need to harvest timber for papermaking and other related industries.

Malaysia is located in tropical region has a year-round of hot and wet climate, which provides the essential conditions to be one of the largest oil palm producers in the world, and blessed with surplus of biomass residues such as empty fruit bunch (EFB). About 15.8 million metric tons of EFB is dumped from palm oil refineries in Malaysia annually (Pande, 1998; Hamzeh *et al.*, 2013). Currently, EFB residues not optimally used are burned in the incinerator at the plant site and their ash is used in oil palm plantations for horticultural application like fertiliser (Vena *et al.*, 2013). However, EFB combustion has been prohibited with growing awareness in environmental protection.

Table 1. Potential agricultural wastes as papermaking feedstock

Type of Agricultural Waste	**Part of Plant Utilise**	**Cellulose Content (%)**	**Lignin Content (%)**	**Fibre Length (mm)**	**Methodology**	**Suitability for Papermaking**	**Ref.**
Sugarcane bagasse	Depithed bagasse	40.5 (±3.2)	27.7 (±3.5)	20-30	Pulping: soda process Alkali: caustic soda Additive: chitosan and cationic starch	Texture of the paper is smooth due to well-grinded of pulp.	(Hamzah *et al.*, 2013)
Bamboo	Depithed bamboo	–	26.8 (±3.2)	27-40	Pulping: Kraft or soda-AQ Alkali: caustic soda, sulfuric acid, anthraquinone (AQ)	Good strength properties due to strong bond of phenolic hydroxyl group in bamboo.	(Pande, 1998; Vena *et al.,* 2013)
Banana	Pseudo stem	–	12.1	600	Pre-treatment: digesting fibre in white liquor Pulping: Kraft process Alkali: caustic soda and sodium sulfide Wrapping paper produced consists of: 1. Banana to wastepaper	Banana fibre was most compatible physically/ chemically with wastepaper compared to bagasse. Different ratios give different physical and chemical characterisation results.	(Ramdhonee & Jeetah, 2017)

					ratios 2. Banana to bagasse ratios		
Pineapple	Leaves	33	22	50	Pulping: soda process Alkali: 15% w/v caustic soda Paper produced consists of: 1. Pineapple to bagasse ratios 2. Pineapple to wastepaper ratios	Pineapple leaves fibre was most compatible physically and mechanically with bagasse compared to wastepaper.	(Sibaly & Jeetah, 2017)
Empty fruit bunch (EFB)	EFB fibre	43.66	25.74	–	Pulping: Kraft process Alkali: caustic soda Additives: microcrystallin e cellulose (MCC)	No significant changes in porosity, grammage, and the opacity is slightly decreased in addition of MCC.	(Ismail *et al.,* 2020)

As a result of the need for sustainable production of palm oil, the EFB is now chopped and returned as a green mulch to the plant site (Fahmy *et. al.*, 2017; Faris, Ainun & Jawaid, 2018).

Nevertheless, EFB is an ideal lignocellulose material with low lignin content in the range of 14.1-30.5%, which ease the pulping process and increase the pulp yield brightness (Pande, 1998). However, since the EFB fibres are shorter than 1 mm in length, the paper manufactured may not as durable as the paper made from wood fibres (Pande, 1998; Hamzeh *et al.*, 2013). In order to improve the added value of EFB residues, used paper (UP) is repulped for the production of EFB/UP paper by mixing EFB to UP with the ratio of 100:0, 75:25, 50:50 and 25:75. The paper samples are denoted with EFB100, EFB75, EFB50 and EFB25, respectively hereafter. The properties of the EFB/UP paper produced is compared with commercialised paper of a grammage of 70 g/m^2. Next, analysis was performed to determine the moisture content, ash content, lignin content, and the cellulose content (Rowel method). The physical and mechanical properties of the EFB/UP paper were characterised according to the TAPPI Standard including grammage, porosity, and tensile strength. Physical conditions of the paper fabricated was also monitored for possible colour changes and growth of mould (microorganism). This research is important in reducing the dependency on wood fibres by utilising the oil palm biomass residues that is abundantly available. Characterisation of the EFB derived fibres and pulps provide crucial foresight into the quality of the paper produced or as alternative feed materials that can substitute the non-sustainable ones.

II. MATERIALS AND METHOD

Oil palm empty fruit bunch was received in bale from Felda Bukit Waha, Kota Tinggi, Johor, Malaysia while the used paper was collected from the offices at the School of Chemical Engineering in the form of printed A4 paper with a grammage of 70 g/m^2. Distilled water was used to mix dry EFB fibres and NaOH during pulping process, while the wooden papermaking mould frame with size of 20 × 26 cm was purchased and used without further modification. Sodium hydroxide (15% w/v, R&M Chemicals), ethanol (70% w/v, Systerm Chemicals) and toluene (95% v/v, Bendosen) were used for extractions using Soxhlet apparatus. Meanwhile, nitric acid (65% v/v, Merck) and ethanol (96% v/v, Systerm Chemicals) were used for cellulose content determination, and sulfuric acid (72% v/v, R&M Chemical) were used in lignin content experiment. All the chemicals were used without further purification.

A. Raw Materials Preparation

EFB was cut to reduce the original fibres to shorter length between 0.5–1 cm using cutting mill SM100 Comfort. The cut EFB were then washed with distilled water to remove undesirable elements, rinsed and dried in a drying oven (LSIS -B2V/VC222 VENTICELL) at 70°C for an hour. The used paper was cut into smaller pieces with sizes between 2-3 cm^2 and soaked in tap water overnight. The EFB fibre to used paper were used in different weight ratio of 100:0, 75:25, 50:50, and 25:75.

B. Pulping and Papermaking Process

EFB on an oven dry basis were digested in a beaker containing 1000 ml of 15% w/v NaOH aqueous solution and slowly heated to 100°C. EFB fibres were continued to be digested in the NaOH solution for 30 minutes at constant temperature of 100°C. The pulp was then washed using distilled water for 2 times, rinsed, and dried at room temperature overnight. EFB to used paper ratios of 100:0, 75:25, 50:50, and 25:75 on oven dry basis were grounded using heavy-duty blender to form slurry for moulding using a sieve tray. Fabricated paper was then dried for 24 hours at room temperature before putting it inside a hot press machine (Cometech Hot Press 50 Tonne) to produce flat and even surface. The paper was pre-heated for 10 minutes prior to hot press with a pressure of 700kPa and temperature of 100°C for 6 minutes.

C. Chemical and Mechanical Analysis

1. Ash content

4g of sample was put in a crucible and placed in a high temperature box muffle furnace (HTBF-17-12L) in an air atmosphere at 550°C for 2 hours. Ash content (TAPPI Standard T211 om-02) measurements for each sample was performed twice without changing the samples and experimental conditions. Ash content is expressed as percent (%) and can be determined using equation (Ramdhonee & Jeetah, 2017) below:

$$\%\ Ash\ Content = \frac{Weight\ of\ ash}{Initial\ weight\ of\ sample} \times 100 \quad (1)$$

2. Cellulose and lignin content

10g of EFB/UP paper sample or fresh EFB was subjected to Soxhlet extraction in the presence of 70% ethanol mixed with toluene (1:2 v/v) and water for 6 hours to remove the extractives. Cellulose content was determined by Kushner-Hoffner procedure (Cordeiro *et al.*, 2004). In brief, 5g of paper sample was dissolved in 125 ml of alcoholic nitric acid solutions (a mixture of 25 ml 65% w/v nitric acid and 100 ml of 96% w/v purity of ethanol) for four cycles within an hour. For each cycle, the alcoholic nitric acid solution is withdrawn, and a fresh amount of the solution was added. Then, the cellulose was washed properly, dried and weighed at the end of the four cycles. Lignin content was determined according to TAPPI Standard T222 om-98 (Properties, 2006) where the carbohydrates (extracted) of 0.2g oven-dry pulp were pre-hydrolysed and solubilised with 2 ml of sulfuric acid (72 wt.%) at 30°C for an hour. The obtained acid-insoluble lignin was filtered and washed off with 70°C hot water, dried at 105°C in an oven until constant weight was achieved, and weighed.

3. Grammage

The grammage measurement was performed using sample with a dimension of 5 cm × 5 cm following TAPPI Standard T-410 om-08 (Timberlake, 2013) and weighed (Sartorius Quintix 224-1S). Measurements were repeated four times and the grammage was expressed as g/m^2 and can be determined in accordance with the following equation:

$$Grammage = \frac{CF \times Mass\ (g)}{Area} \quad (2)$$

where, CF = conversion factor (10,000)

Table 2. Conversion factor (Timberlake, 2013)

Units of measurement	**Area**	**Conversion factor**
Gram	cm^2	10,000
Gram	$in.^2$	1,550
Indicated weight (lb) for 500-sheet ream	cm^2	9,070
Indicated weight (lb) for 500-sheet ream	$in.^2$	1,406

4. Porosity

Porosity was used to analyse the volume of air flowing through the test sample, as well as any potential diffusion of air through the surface. Scanning Electron Microscope (SEM) (Ultra-High-Resolution Schottky SU7000) was used to capture the morphology of the sample at 15kV accelerating voltage (Hamzeh *et al.*, 2013). Prior to SEM analysis, samples with the dimensions of 1 cm x 1 cm were coated with ultra-thin platinum coating (Heu *et al.*, 2019)using sputter coater (POLARON Thermo VG Scientific SC 7620) . A carbon source was mounted in a vacuum system between two high-current electrical terminals (Faith, Horsfield and Nazarov, 2006). After the carbon source was heated for 10-15 minutes, a fine spray of carbon was coated over the paper sample under plasma current of 40 mA with an air pressure of 500 Pa for an hour.

Images were captured at magnifications of ×50, ×100, and ×200 to study the moprhology, compactness, distribution, and porosity of the paper samples. Pore size and particle size were analysed and estimated using ImageJ software (version 1.53e) (Muchorski, 2006).

5. Tensile strength

Tensile strength was conducted according to TAPPI T494 om-01 (Muchorski, 2006) to measure the sample needed to rupture within the force apply according to the suitable recommendation conditions using a universal tensile machine. Sample was cut into 30 mm (W) and 110 mm (L) and was clamped on the load with clamp distance of 100mm at a speed of 25mm/min, strain rate of 25-5mm/min and load of 2.2N. The testing was used to determine break and peak force (N), break and peak strain (%), time to failure and time to peak in unit second.

6. Physical changes observation

Each paper sample was cut into small pieces of sizes (10cm x 15cm or 10cm x 18cm), kept in a container without lid and left at room temperature without humidity control to monitor physical changes such as colour and mould development. The observation was performed for 4 consecutive weeks.

D. Moisture Content

This test was used to determine the moisture content (TAPPI Standard T264 cm-97) of the fabricated EFB/UP paper. At least 9 cm² of sample was obtained from paper produced using different ratio of EFB/UP, raw EFB, and raw used paper. Each sample was weighed to record the initial weight before placed in Sartorius MA35 moisture analyser balance operating at 105°C for 15 minutes. Measurement was repeated three times without changing the equipment's conditions to increase the accuracy of the results. Next, final weight of the sample was recorded, and percentage of moisture content can be obtained from equation (Ramdhonee & Jeetah, 2017) below:

$$\%\,Moisture\ Content = \frac{Weight_f - Weight_i}{Weight_f} \times 100 \qquad (3)$$

where $weight_f$ and $weight_i$ indicate final and initial weight, respectively.

III. RESULTS AND DISCUSSION

A. Physical Appearance of EFB/UP Paper

Figure 1 shows the paper samples produced with different EFB to used paper ratios. The colour and pigment of the papers with increasing EFB percentage appeared darker due to the natural EFB colour that has not been bleached. Bleaching process can help to improve and brighten the colour of the pulp. Paper made with only 25% EFB fibre is brighter compared to papers made from higher EFB percentage due to the original brightness of used paper. The dimensions of all the papers produced were 17 × 26 cm.

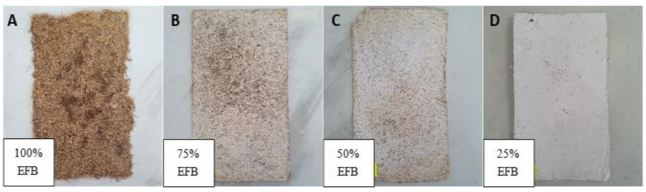

Figure 1. Physical appearance of EFB/UP papers with EFB content ranging from 25 to 100%

B. Chemical Analysis and Moisture Content of Raw EFB Fibre and EFB/UP Paper

Chemical compositions and moisture content of the raw EFB (non-extractive), raw used paper and mixed ratios of EFB/UP papers are presented in Table 3.

Table 3. Chemical compositions and moisture content of raw materials in different ratios of EFB/UP papers

Sample	Fibre Composition (% w/w)	Moisture Content (%)	Ash Content (%)	Cellulose Content (%)	Lignin Content (%)
EFB only	–	19.62 ± 2.25[a]	2.02 ± 0.06[b]	52.26 ± 2.74[b]	20.00 ± 1.21[b]
UP only	–	9.86 ± 1.83[a]	2.55 ± 0.11[b]	–	–
EFB:UP	25:75	7.28 ± 0.16[a]	7.49 ± 0.54[b]	42.54 ± 2.48[b]	12.50 ± 0.73[b]
	50:50	8.68 ± 0.44[a]	8.85 ± 0.40[b]	43.92 ± 2.77[b]	19.50 ± 1.96[b]
	75:25	9.20 ± 0.02[a]	6.16 ± 0.20[b]	44.26 ± 2.03[b]	24.00 ± 2.57[b]
	100:0	9.86 ± 0.34[a]	2.28 ± 0.28[b]	45.22 ± 2.69[b]	26.50 ± 2.84[b]

[a]Average values standard deviations (±) of triplicate experiments
[b]Average values of duplicate experiments

Commercial papers are produced to an absolute moisture content between 2 and 6% (Nienke *et al.,* 2022). Moisture content provides an indication on the hygroscopic characteristic of paper as the length and width of a paper can change depending on relative humidity of the surrounding environment. The moisture content of paper also affects its various mechanical, surface and electrical properties, which should be taken into account when storing papers in warehouses. Moisture content of raw EFB was recorded the highest of 19.62% (on dry basis), compared to raw used paper (9.86%) and papers produced from the combinations of EFB and UP. Moisture content of the EFB/UP papers was found increasing with the amount of the EFB used in the paper production, ranging from 7.28 to 9.26%. Moisture content of the raw EFB recorded in this study was significantly higher than the results obtained by Rosl*i et al.* (Rosli *et al.*, 2017), which reported a lower moisture content of 9.51%. Changes in moisture content depend on several factors including climate circumstances, feedstock variety, soil type, and sample storage conditions (Ramdhonee & Jeetah, 2017). Meanwhile, the moisture content for raw used paper was in agreement with Ramdhonee *et al.* (Ramdhonee & Jeetah, 2017).

Ashes are the trace substances that remained after incineration or burning. The ash content of the raw EFB fibre (2.02%) was consistent with the value stated in the literature (Rosli *et al.*, 2017). The ash content of raw used paper in this work (2.55%) is lower than the reported value of 17.7% (Ramdhonee & Jeetah, 2017), implying a lower inorganic residue from papermaking chemicals. Higher ash contents varied from 2-9% in the EFB/UP papers produced might be attributed to residual dirt in the raw EFB, different residues from chemicals used to make the paper, metallic debris from pipes during the washing process, or machinery used to cut the EFB into shorter lengths (TAPPI, 2007). A lower ash concentration is desired to produce papers with increasing strength.

Weight loss (%) was used to determine the cellulose and lignin content (Mansor *et al.*, 2019) in raw EFB and each mixed ratios of EFB/UP paper. Cellulose is a main structural element in pulp and paper industry. There is randomly oriented cellulose molecule in the EFB and tend to form crystalline regions (Rowell, Pettersen & Mandla, 2012). From the result, fresh EFB fibre has the highest cellulose content of 52.26% followed by the paper made from 100EFB (45.22%), 75EFB (44.26%), 50EFB (43.92%) and 25EFB paper (42.54%). Findings were in agreement with the results reported by Ismail *et al.* (Ismail *et al.*, 2020) with a cellulose content of 43.66%.

The lignin content of fresh EFB found in this study was about 20%, that is in close agreement with the findings by Faris *et al.* (Faris *et al.,* 2018) and Ismail *et al.* (Ismail *et al.*, 2020). This demonstrated that EFB is feasible for Kraft or soda pulping due to the low percentage of lignin. The subsequent bleaching process is much easier without having to use a lot of chemicals (Ferrer *et al.*, 2011).

C. Grammage

The grammage of paper is the mass of paper of a particular unit area (Widiastuti & Elfi, 2018). Consumers will consider this characteristic when purchasing paper. Depending on the ultimate usage of the paper, the grammage can be altered by adding or reducing the amount of pulp used per sheet. Hypothetically, increasing the grammage of the paper produced will improve its physical and mechanical characteristics. However, more pulp will be used for every sheet of paper to be produced if high grammage is demanded (Sibaly & Jeetah, 2017). In this work, the EFB/UP paper produced is compared with commercial paper of 70 g/m^2 and the results are shown in Table 4. Paper fabricated using 25% EFB has an average grammage close to the commercial paper. Papers produced with higher EFB percentage resulted in high grammage between 400 to 700 g/m^2 due to higher mass of EFB fibre.

Grammage results of higher EFB ratio depicted in Table 4 are excessively contrast with the results obtained by Sibaly & Jeetah (Sibaly & Jeetah, 2017) except for the paper produced using 25% EFB. In their study, the grammage value of mixed used paper and pineapple were almost comparable to commercial paper of 70 g/m^2, with an average grammage between 60.42–63.60 g/m^2. The results were nearly identical with the study about natural wrapping paper made from banana peel with the addition of essential oils (Widiastuti & Elfi, 2018). In the present work, the grammage was found to rise sharply in papers fabricated using 50% and higher percentage of EFB. It is indeed conceivable that the inconsistency in grammage measurements is due to the fact that more pulp was utilised to produce the paper.

All of the exceeded grammage values obtained for 50% EFB, 75% EFB, and 100% EFB paper met the standards stipulated by International Organization for Standardization (ISO), which stated that paper with a grammage higher than 200 g/m^2 is categorised as paperboard, board, or corrugated board type (Richard, Derek & Mark, 2003) with high number of the fibres. The amount of pulp used in the papermaking process is therefore crucial as it affects the specific thickness and eventually the grammage of the paper. The greater the amount of pulp used, the greater the thickness, and therefore the grammage will increase (Widiastuti & Elfi, 2018).

Table 4. Average grammage of papers produced from different EFB:UP ratio

Type of Paper	**Ratio of Fibre Composition (% w/w)**	**Average Grammage (g/m²)**
EFB:UP	25:75	59.8 ±1.0
	50:50	660.7 ±41.9
	75:25	685.6 ±26.8
	100:0	433.4 ±6.6

D. Analysis of Fibre Length and Pore Size

Fibre length of EFB was carefully measured from SEM images captured at 50× and 200× magnifications using the ImageJ software. Table 5 summarised a comparison of EFB morphological properties found in this study and Ferrer *et al.* (year) (Ferrer *et al.*, 2011). Average fibre length and fibre diameter for each EFB/UP paper are presented in Figure 2.

Table 5. Comparison of morphological properties of EFB fibres based on present study and the findings from literature

Parameter	EFB fibre (this study)	EFB fibre (Ferrer *et al.*, 2011)
Fibre length, mm		
Minimum	0.30	0.27
Maximum	2.50	1.48
Average	1.16 ±0.82	0.53
Fibre diameter, µm		
Minimum	4.40	–
Maximum	16.60	–
Average	9.20 ±4.80	14.00

The average value of fibre length was found between 1 to 1.2 mm for all the papers produced with different ratio of EFB/UP paper. The fibre length was longer than the one reported by Ferrer *et al.* (Ferrer *et al.*, 2011), which was 0.53 mm in average. However, the average diameter of 50% (10.2 µm (±2.2)) and 100% EFB (13.8 µm (±4.0)) papers found in this study were comparable with the findings by Ferrer *et al.* (Ferrer *et al.*, 2011), with an average diameter of 14.0 µm. However, the diameter of fibre length for 25% EFB (5.3 µm (±0.9)) and 75% EFB (6.0 µm (±1.6)) was considered low. The discrepancy in fibre length was most likely due to the diameter of each fibre arranged from one end to the other, with the highest diameter measured at the centre of the fibre (Gunawan *et al.*, 2009).

Pore size was determined using ImageJ software by generating a clear threshold. Pore particles can be analysed when a threshold image is presented and an image with a number of outlines is auto-depicted by the software, indicating the possibility of pore particles appearing on a specific EFB/UP paper ratio. Following that, the ImageJ software will create a table with all the area of pore sizes listed, as well as the average area of the pore size. The threshold value of 90.1% was used for all the different EFB/UP papers made in this experiment.

There was a total of 129 possible pores counted for 25EFB paper with the average area of pore size of 0.35 mm² (±0.38). The EFB/UP paper made from 50% EFB and 50% used paper were found to have 137 counted possible pore to be appear with the average area of 0.49 mm². Meanwhile, both 75EFB (375 counted pore particles) and 100EFB (234 counted pore particles) have an average area of pore size 0.37 mm² (±0.32). The small variations from the average are of pore size obtained were mostly due to the uneven distribution of pulp when moulding the paper (Soloi & Hou, 2019).

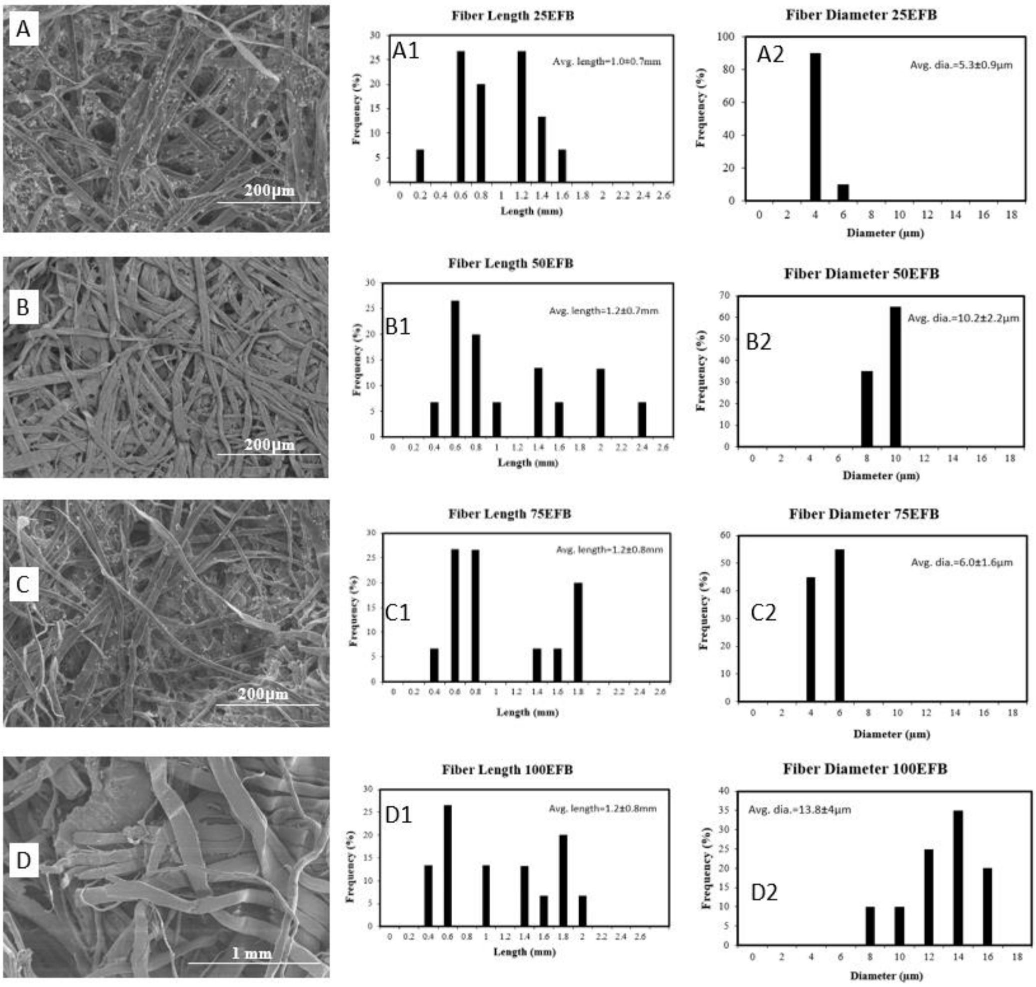

Figure 2. SEM images, distribution of fibre length (A1 to D1) and diameter (A2 to D2) of papers produced from (A) 25EFB, (B) 50EFB, (C) 75EFB, and (D) 100EFB. Paper with higher composition of EFB showing higher fibre diameter.

E. Tensile Strength

Tensile index of the fabricated paper was calculated and the results revealed that the tensile index increased with the lower percentage of EFB fibre in the pulp composition (Figure 3). The paper with the lowest tensile index of 0.16 Nm/g was found to be produced entirely from EFB fibre (100% EFB), while the 25EFB paper has the highest tensile index of 2.01 Nmm/g. This implied that the presence of used paper allowed better bonding strength during paper production, resulting in an optimal tensile index. Additionally, a higher tensile index may denote a lower cellulose content (Aremu, Rafiu & Adedeji, 2015).

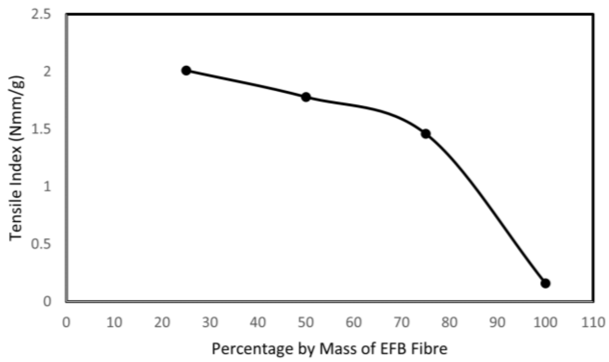

Figure 3. Tensile Index for EFB/UP paper with ratio by mass of 25EFB, 50 EFB, 75 EFB, and 100 EFB

F. Physical Changes of EFB/UP Papers

Each paper sample fabricated was monitored for possible colour changes and mold development for four weeks at room temperature without humidity control or light. Results shown in Figure 4 revealed that no major colour changes occurred on all the paper samples in addition to no trace of fungal growth. This might be due to the successful removal of undesired components such as soil, insects, and other fine particle elements from the fresh EFB prior to pulping and papermaking.

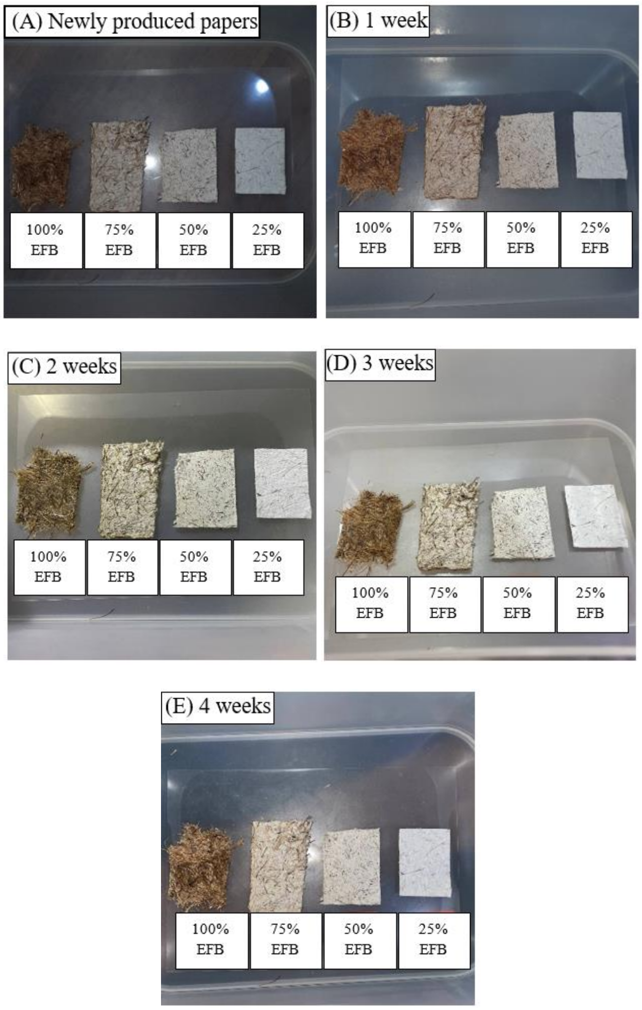

Figure 4. No trace of fungal growth or major colour changes on all the papers produced during the 4 weeks of observation. Some slight variation in colour due to photographic lighting sources

IV. CONCLUSIONS

In conclusion, empty fruit bunch (EFB) as an alternative non-wood fibre resource for pulping and papermaking is successfully carried out in this study. It was found that 25EFB paper exhibited good physical appearance and was almost comparable to commercial paper with grammage of 59.8 g/m² and suitable for writing. Paper fabricated using a higher EFB ratio exceeded the grammage of commercial paper (70gsm), and more suitable in producing paperboard, board, or corrugated board. The moisture and ash content of each EFB/UP ratio also indicated different pattern of results where the ash content of 25% EFB, 50% EFB, 75% EFB, and 100% EFB paper are 7.49%, 8.85%, 6.16%, and 2.28%, respectively. Lignocellulosic content of raw EFB fibre obtained in this study have shown a slightly higher cellulose but lower lignin content compared to findings reported in literature. The research also revealed that EFB wastes, which are often discarded after harvesting, contain significant cellulose along with low lignin content, making it suitable as an alternative low-cost feedstock in pulp and paper production. The average fibre diameter determined for 25% EFB, 50% EFB, 75% EFB, and 100% EFB paper are 5.3 µm (±0.9), 10.2 µm (±2.2), 6.0 µm (±1.6), and 13.8 µm (±4.0), respectively. The paper having the least number of pores was the 25EFB with a total of 129 counted pore particles and an average area of 0.35 mm². 25EFB paper had the highest tensile strength, with a tensile index of 2.01 Nmm/g. There were no major colour changes on all the paper samples. The surface of the paper samples was also free from fungal growth when stored under room temperature with no humidity and temperature control for four weeks. Overall, the pulp produced from empty fruit bunch is suitable to be used in the papermaking industry. For improvement of work in the future, bleaching process can be further done to further remove excess amount of lignin content and produce brighter paper made from EFB fibre.

V. ACKNOWLEDGEMENT

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