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Pulp and Paper Potentials of Alkaline Peroxide Pre-Treated of Oil Palm Waste and Industrial Application

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.74430>

Abstract

This chapter explores the potentials of the alkaline peroxide pre-treated oil palm vascular bundle (oil palm waste) in the industrial production of pulp, paper and other cellulosic products like microcrystalline cellulose. Management of this escalating waste is a herculean task and creates environmental hazards hence urgent action is needed to create value out of these waste biomass. The pulp and paper industry being a large consumer of lignocellulose materials preferred the use of coniferous and deciduous trees for pulp production and papermaking because their cellulose fibres in the pulp make durable paper. In addition to this, the global population explosion and the economic development has resulted in the significant increase in demand for paper. With improvements in pulp processing technology through the use of environmental benign technology like alkaline peroxide pre-treatment it has been considered as suitable for paper pulp and other cellulose based products such as microcrystalline cellulose. Characterization of the alkaline peroxide pre-treated oil palm vascular bundles using the scanning electron microscope (SEM), Fourier transmission infra-red (FTIR) spectroscopy and X-Ray Diffraction (XRD) analyses confirm the micro-sized cellulose fibres. Use of these lignocellulosic materials can reduce the burden on the forest while supporting the natural biodiversity.

Keywords: alkaline peroxide, FTIR, oil palm waste, pulp and paper, SEM, oil palm vascular bundle, industrial production of pulp and paper

1. Introduction

As the global demand for palm oil increases in the global markets, many tropical countries like Malaysia, Indonesia, Nigeria and others, have invested heavily in its plantation and production of Crude Palm Oil (CPO) and Palm Kernel Oil. Indonesia is the world's largest producer of palm oil contributing about 44% of the total world supply, which is followed by Malaysia, with 43% of the total world supply of palm oil (year 2006–2009) [1, 2]. The palm oil industry contributes \$7.3 billion annually to the Malaysian GDP through export [3]. In Malaysia, over 75% of oil palm plantation in Malaysia spread within four states, which include, Sabah, Johor, Pahang and Sarawak, each of which has over half a million hectares under cultivation. It was reported that about 4.3 million ha lands were utilized for oil palm plantations in 2007 which has increased to 4.49 million hectares in 2009 and it is predicted that the annual production will be increased to 50 million tons by the year 2030 [4, 5]. With the proposed increase in the oil palm plantation, there is expected increase in the oil palm waste generation. From the present estimated 83 million tonnes (dry weight) of oil palm waste generated, Awalludin and coworkers [5] reported that, it is expected to rise by 40% dry weight by 2020. From the oil palm production activities, 10% of the products goes to the oil palm produce while the remaining 90% are considered as waste biomass [6]. These waste biomass include, Oil Palm Trunk (OPT) generated after 25 years replanting scheme and Oil Palm Fronds (OPF) generated during monthly pruning during and replanting season. Although these are either used as main source of energy for power generation in oil palm mills or as organic fertilizers for natural decomposition. OPF which is the largest waste generated through the activities of the oil plantation is reported to generate about 15 tons per hectare of dried OPF and are pruned and left to rot away at the plantation site [7]. This has been reported to constitute environmental menace to the dump sites [8]. Mushtaq and coworkers [8] reported that during oil-palm fruit harvesting, about 44 million tonnes of OPF dry weight are generated. The management of these enormous wastes has demanded the attention of researchers to proffer ways of value addition. Other oil palm waste generated is empty fruit bunches (EFB) from the oil mills, oil palm shells, kernel cake and mesocarp fibres [9]. Apart from palm oil mill effluent (POME), other oil palm wastes generated are lignocellulosic wastes which represents an extraordinarily large amount of renewable bio-resource available in the universe and has wide array of applications as raw material especially for cellulose based materials [10].

The quality of the cellulosic products from this cellulose depends on the source of the original cellulose, the type of treatment and the kinds of the extraction procedures [11]. The effective utilization of lignocellulosic is conversely, not totally devoid of challenges. Among the range of the challenges associated with the use of lignocellulosic biomass apart from byproducts generated during pretreatment are, resistance of the plant cell wall due to integral structural complexity of lignocellulosic fractions and strong hindrance from the inhibitors [12]. Similarly, the knowledge of suitable pretreatment method and extent of cell wall deconstruction for generation of value-added products are equally very important in the choice of the pretreatment methods. The pretreatment techniques for overcoming biomass resistance could be selected over an array of methods which include: avoidance of cellulose fibre size reduction, preservation of the hemicellulose, minimization of by products, reduction in energy consumptions,

use of low cost pretreatment catalyst and should justify the cost of downstream processing steps [13]. Oil palm lignocellular wastes fibres have been proven to be suitable as ideal source for pulp and paper, cellulose based micro and nanofibres. It's a fast growing accumulation that has been considered as an advantage. Based on extensive studies on the use of cellulosic plant fibres for various industrial applications, oil palm wastes are reported as being sustainable, reusable, and eco-friendly. Research studies into the properties of the oil palm wastes show that the processing is cheap and low cost since they are considered as wastes. The polymer reinforced green composite obtained by their application has been characterized as having low energy consumption, light weight, low environmental hazard, and are renewable [14].

1.1. System with alkaline peroxide pretreatment of lignocelluloses

Hydrogen peroxide is a mild oxidant [15]. Its highest efficiency in bleaching and delignification is observed when the reaction is conducted in alkaline medium. In the presence of sodium hydroxide, and absence of any stabilizing agents like diethylenetriamine penta- acetic acid (DTPA), or ethylene diamine tetraacetic acid (EDTA) etc. hydrogen peroxide is unstable [16]. Hydrogen peroxide readily decomposes (Eq. 1) to generate more active radicals such as perhydroxyl acid, hydroxide ions, superoxides, which play prominent role in dissolving lignin hence releasing the fibre for paper making [17]. The mechanism of alkaline peroxide delignification reaction of hydrogen peroxide revealed that it is strongly pH dependent [18] with an optimum at pH 11.5–11.6, pKa for the dissociation:



Under these conditions, the active species responsible for the elimination of chromophoric groups from lignin are hydroperoxide anion (HOO⁻) [19]. **Table 1** shows the list and characteristics of active radicals and anions from hydrogen peroxide decomposition in alkaline medium [20].

H₂O₂ decomposition products such as ·OH and O₂^{-·}, are the primary lignin oxidizing species. The delignification reaction witnessed the evolution of O₂ from the reaction mixture indicating H₂O₂ decomposition. The alkaline peroxide delignification procedure is a lignin-retaining bleaching of mechanical, thermomechanical, chemimechanical, and semichemical pulps [21].

Reactants	Name	Type	Nature	Function	pH range
HOO ⁻	Hydroperoxide anion	Anion	N	Reductant	Alkaline
OH ⁻	Hydroxide ion	Anion	N		Alkaline
HOO•	Hydroperoxyl Radical	Radical	E	Oxidant	Acidic
HO•	Hydroxyl radical	Radical	E	Oxidant	Acidic
O ₂ ^{-·}	Superoxide anion radical	Radical, Anion	N	Oxidant	Alkaline/neutral

Source: [20].

Table 1. Active radicals and anions from H₂O₂ decomposition in alkaline medium.

If the reaction contribution is not properly controlled, these radical materials are likely to re-deposit on the biomass surface. Pulp brightness may be achieved by either lignin removal (delignification) or lignin decolonization [22]. This anion was found to be a strong nucleophile that is site specific, during bleaching, preferentially attacks ethylenic and carbonyl groups present in lignin. As a consequence, such chromophores as quinones, cinnamaldehyde, and ring-conjugated ketoses are converted to non-chromophoric species [20]. On the other hand, radical species such as hydroxyl radicals ($\text{HO}\bullet$) generated from the hydrogen peroxide alkaline decomposition, are responsible for delignification and solubilization of hemicelluloses [21]. Sequel to the mechanism of alkaline peroxide delignification, Gould [19] reported the use of alkaline peroxide in the delignification of agricultural residues to enhance enzymatic conversion of the cellulose-rich residue to glucose. According to the report, approximately one-half of the lignin is dissolved. Most of the hemicellulose present in agricultural residues such as wheat straw and corn stover was solubilized when the residue was treated at 25°C in an alkaline solution of hydrogen peroxide.

2. Characterization of alkaline peroxide pre-treated oil palm waste fibre

Screening the effect of the alkaline peroxide pre-treated vascular bundle fibre particles was carried out with three different alkaline peroxide concentrated liquors: low (H_2O_2 : NaOH; 1.5:1.0), medium (H_2O_2 : NaOH; 2.5:2.0) and high (H_2O_2 : NaOH; 5.0:4.0) at alkaline peroxide pretreated oil palm frond vascular bundles (AP-OPF VB) reaction duration ranging from 10 to 60 min, with 0 min serving as control.

After the reaction period, the solid pulp was dried at 103°C and subjected to Fourier Transform Infrared (FTIR) spectroscopy to elucidate the changes in the functional groups predominating the samples before and after pulping. To further exploit the effect of the AP pretreatment, extracted cellulose fibre, crystallinity and the thermal analysis through the study of the thermogravimetry analysis TGA and derivative thermogravimetry (DTG) as reported by Lamaming and coworkers [22] were used to characterize the extracted cellulose fibres in terms of thermal stability, miscibility, and the reaction enthalpy that occur during the temperature-dependent phase transition. Also the TGA was used to characterize the thermal stability of materials through the study of the thermal degradation of the fibre at varying temperature. The knowledge of the X-ray diffraction pattern XRD of the cellulose fibres is used to estimate the purity of the AP treated biomass. This is based on the crystallinity values. The result and surface morphology of the produced OPF VB fibres and Handsheet were studied with the aid of the scanning electron micrograph (SEM).

2.1. Evaluation of the pulp fibres from AP pre-treated OPF vascular bundles

Two-way ANOVA of the AP level and pretreatment duration as independent factors on the screened pulp properties (screen yield, kappa number and the CSF), the paper mechanical properties (Tensile, Burst and Tear indexes) and ISO brightness shows significant difference

in the pretreatment study. The result shows that the time factor, the AP pretreated concentration factor and the interactive effect of the time and the AP treatment factors are statistically significant at 95% confidence level. This development led to the determination of the level of significant effect through post hoc test conducted on the AP pretreatment on the pulp and strength properties of the formed handsheet with the different alkaline peroxide dosage as displayed in **Table 2**. The significant differences in the AP concentration levels for the homogenous subset of all the independent variables namely: Screened yield, kappa number, Canadian freeness test (CFS), Tensile, Burst and Tear indexes and ISO brightness (**Table 2**) shows that the pulp and paper properties increased with an increase in the AP concentration. The result shows best pretreatment is obtained for papers prepared at a high concentration of AP pretreatment. The differences among the alkaline peroxide concentration pretreatment levels were tested, by using Duncan Multiple Range test and the significant distinctions are denoted by letters a, b, and c (**Table 2**).

From the result obtained, there is generally increase in the pulp and paper properties investigated with the AP pretreatment of the oil palm vascular bundles, with the increase in the AP concentration. The increase in the pulp and paper properties as observed with increase in the AP concentrations is attributable to the dissolution of lignin fragment and the loss of some extractives from the OPF VB. This shows that an increase in the concentration of AP results in gradual reduction in lignin molecule and hemicellulose removal. A reverse trend, however, was obtained for high AP concentration in the screened yield. A general drop in the pulp screened yield between 50.44 and 57.70% was apparent at high AP concentration. This observation could be attributable to the gradual increase in the rate of lignin dissolution resulting in the lignin modification and hemicellulose loss as conspicuously shown on the result obtained from the TGA/DTG curves and FTIR spectra (**Figures 1–4**) respectively. The decline in the screened pulp yield obtained at high AP concentration is also attributable to the high rate of micro-to-nano scale cogenerated fibrils that escaped the P200 screen during screening stage, resulting in low screened pulp yield. This presence of these fines particles enhances the water retention of the pulp web resulting in the low value of the CSF as shown in **Table 2** at high AP concentrations. Conversely, an increase in alkaline peroxide level is attributable to better extent of lignin removal. As a result, an increased amount of delignification agents was available to access the more remote chromophoric groups within the OPF structure. This

Treatment	PH	Yield (%)	Kappa Number	CSF (ml)	Tensile Index (mN/g)	Burst Index (kpa m ² /g)	Tear Index (mN m ² /g)	ISO Brightness
Low	13.45	40.21b	114.55a	780a	1.59c	2.87c	2.33b	28.528a
Medium	13.70	42.67a	101.10b	550b	9.085b	5.95b	5.37a	27.806b
High	14.00	38.07c	91.20c	241.67c	13.34a	7.90a	5.63a	24.183c

Means within a column with different letters are significantly different at P < 0.05.

NB: a = Highest significant; b = Lower significant; c = Least significant.

Table 2. DMRT for AP significantly different effects on pulp and paper properties.

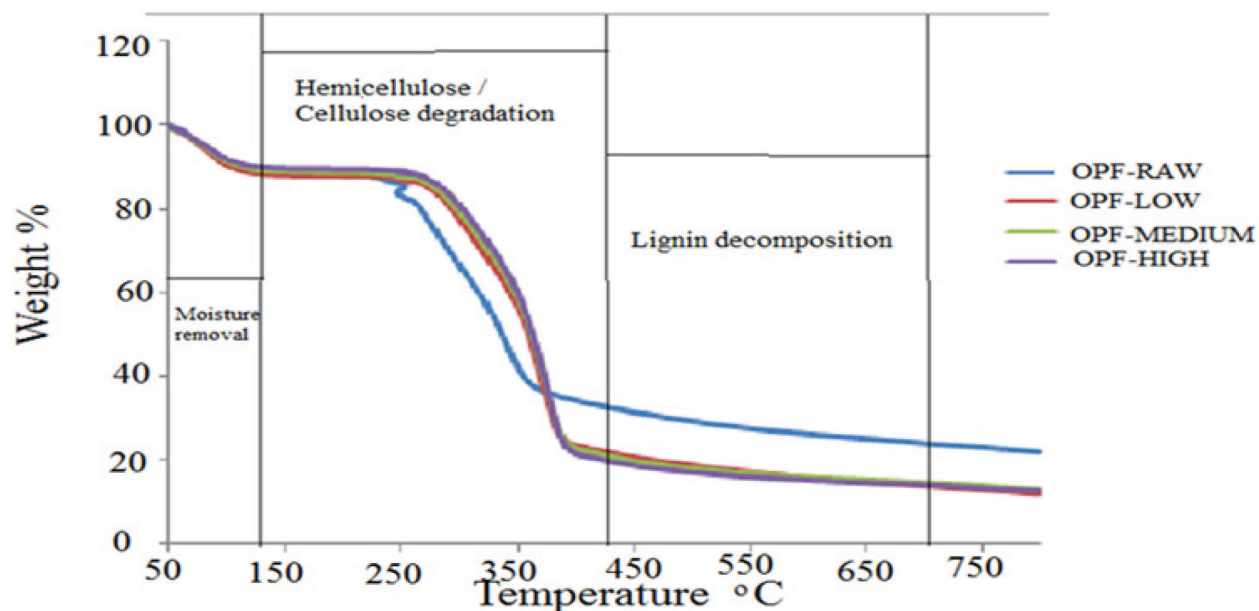


Figure 1. TGA curves for OPF vascular bundle fibres [7].

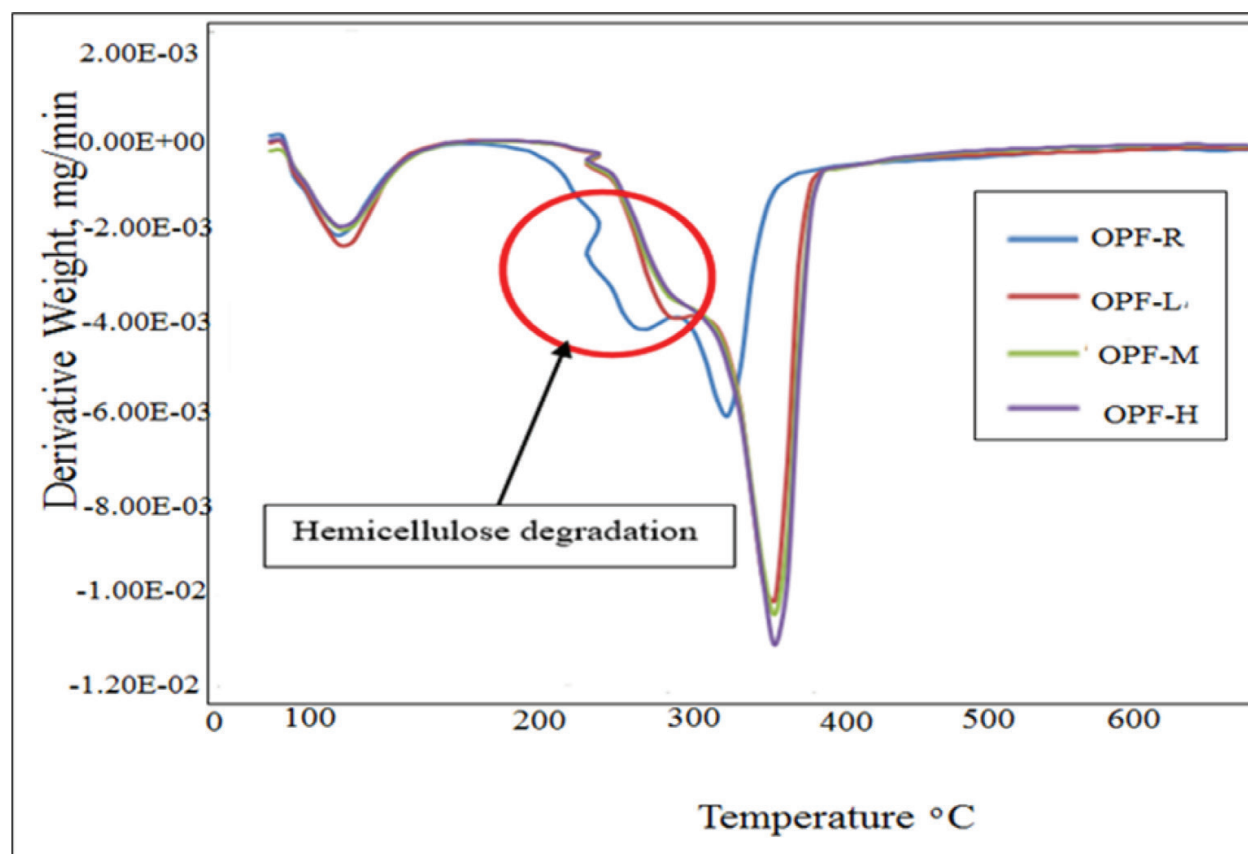


Figure 2. DTG curves of the raw and extracted OPF vascular bundle fibres [7].

contributed to the low Kappa number obtained at high AP concentration **Table 2**. Despite the general decrease in the Kappa number with time with the increase in the concentration of chemical charge, the high Kappa number results (**Table 2**), is attributable to the weak oxidizing

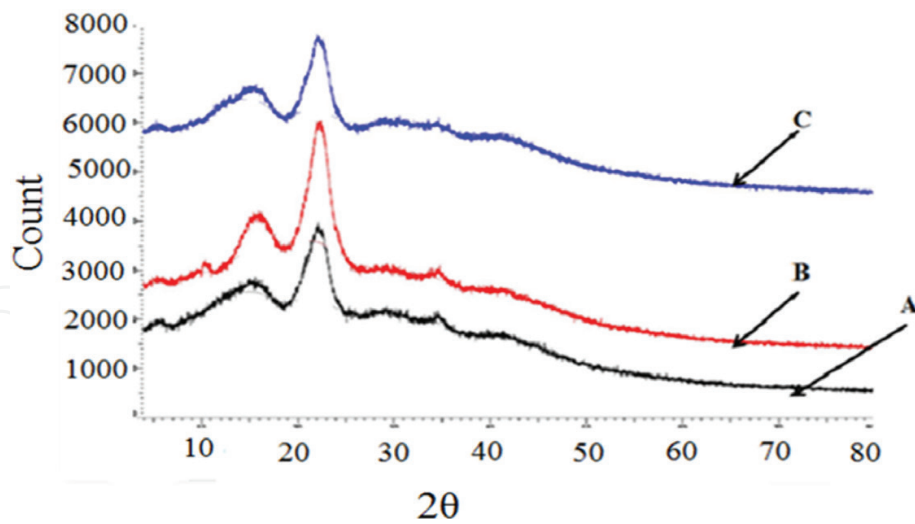


Figure 3. X-ray diffractometry patterns of APMP pulp from OPF vascular bundles [7].

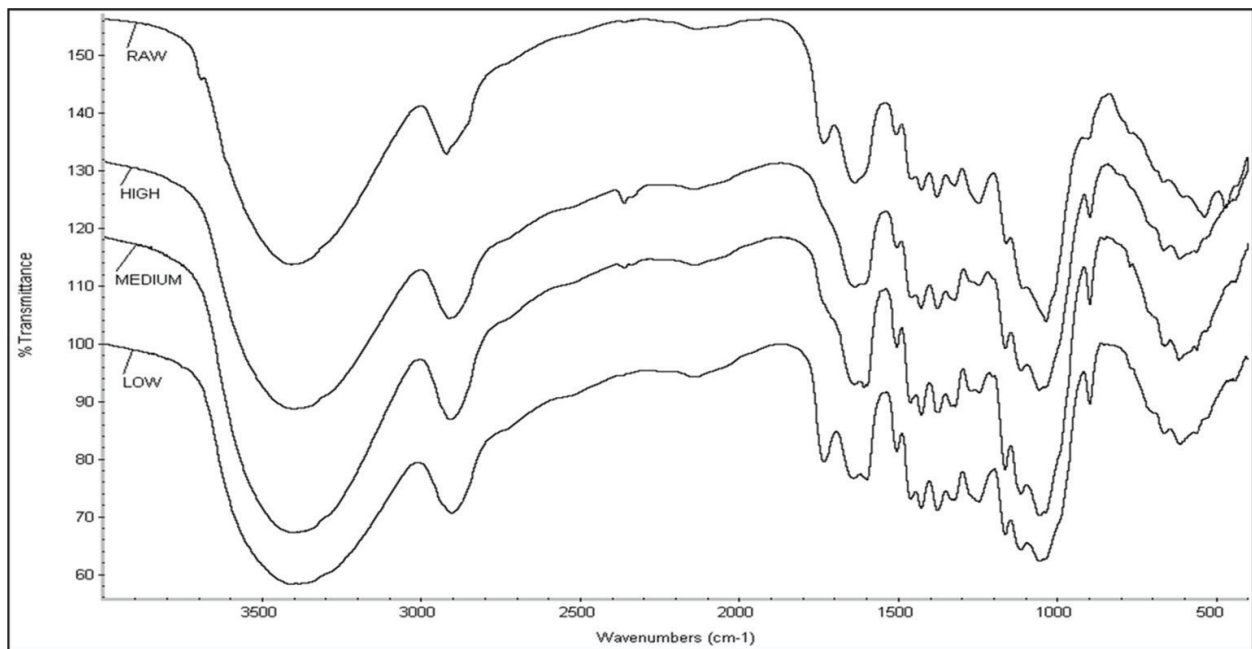


Figure 4. FTIR spectra of OPF vascular bundle fibres at different AP pretreatment.

power of alkaline peroxide [23]. About 50% lignin was reportedly removed from a couple of lignocelluloses biomass (corn stover, oak shavings, kenaf, straw and wheat straw, which has been reported possessed similar morphological properties) treated with 2% (w/v) solution of alkaline peroxide [15]. Also, the same observation was reported when alkaline peroxide was optimized at 8.6% (w/v) [19]. With the treatment of alkaline peroxide for wheat straw, 60% reduction in lignin was recorded [23]. A similar result was reported by sun and coworkers [17] that treatment with the alkaline solution of hydrogen peroxide on rye straw resulted in 60% delignification. The overall result shows a reduction in the lignin by 25.56, 32.05 and 38.43% for pulp generated from the low, medium and high AP concentration pulping system. Since Kappa number is a measure of the total amount of residual lignin in the pulp that is

oxidizable with KMnO_4 , its value is used to determine the residual lignin content in the pulp. Result in **Table 2** also shows that the optical properties are significantly affected by the AP pre-treatment concentration. The decrease in brightness at high concentrations of the AP liquor is attributable to the redeposition of the alkaline leachate on the surface of the biomass hence resulting to the phenomenon of alkaline darkening. This is similar to the observation reported by Liu and co-workers [24].

3. Characterization of alkaline peroxide pre-treated OPF fibres

The extracted fibres were next characterized for their thermal properties and functional groups.

3.1. Thermal characterization of OPF AP pulp

Thermogravimetric analysis (TGA) was measured to access the thermal stability of the extracted fibres. It provides quantitative information on weight change during heating process [25]. From the result shown in **Figures 1 and 2**, the thermogravimetry TGA and derivative thermogravimetry DTG curves obtained for both the raw and the extracted OPF fibres at different AP concentrations. Where (a) untreated represents fibre OPF-R, (b) Fibre pre-treated at 1.0% NaOH: 1.5% H_2O_2 —OPF-LOW, (c) Fibre pre-treated at 2.0% NaOH: 2.5% H_2O_2 —OPF-Medium, and (d) Fibre pre-treated at 4.0% NaOH: 5.0% H_2O_2 ; OPF-High AP concentrations. From the graph, the initial weight loss was observed to occur between 50 and 106°C for the raw sample while the weight loss for the extracted samples were observed between 50 and 110; 50 and 118 and 50 and 119°C for cellulose from low; medium and high AP concentrations, respectively. This first stage of weight loss, which is not accompanied with samples thermal degradation, corresponds to loss in the volatile materials and vaporization of water because of the hydrophilic nature of the lignocellulose fibres in all the samples [26]. The second stage of weight loss, was observed between 230 and 282; 262 and 366; 254 and 366; and 270 and 366°C for raw and the extracted fibres at low, medium and high AP concentrations, respectively. This corresponds to hemicellulose, pectin and cellulose degradation as previously found by Eriksen and coworkers [27].

From DTG (**Figure 2**), the maximum thermal degradation peak corresponds to 342; 366; 374 and 382°C for untreated OPF fibre and cellulose fibres obtained at low, medium and high AP concentrations, respectively and this corresponds to the decomposition temperature of cellulose [28]. This weight loss was attributed to thermal depolymerization and cleavage of the glycosidic linkages of cellulose [29]. From the DTG curves (**Figure 2**), the lower temperature peak at around 290°C was observed from raw (untreated fibre) and AP extracted fibres at H_2O_2 : NaOH 1.5:1.0, corresponds to the decomposition of hemicellulose [25]. This temperature peak was found to shift to a higher temperature and remained as a shoulder for AP-treated fibres at H_2O_2 : NaOH of 2.5:2.0 and H_2O_2 : NaOH of 5.0:4.0, indicating partial removal of hemicellulose from the fibre. From the DTG result it could be deduced that, the extracted cellulose has higher thermal stability than the raw OPF fibre. The third decay stage of the thermal

decomposition graph, presents thermal degradation peaks of lignin compound as a result of the breakdown of ether and carbon–carbon linkages [30]. With further heating beyond 400°C, all the fibres at the specified AP concentrations, had residual weight of approximately 27.47, 12.71, 13.55 and 13.34% for untreated OPF fibre and cellulose fibres obtained at low, medium and high AP concentrations, respectively. The residual char obtained at the end of the heating exercise was ascribed to the combination of the residual lignin and ash in the samples. This is in line with the result of Rosa et al. [30], and Sonia and Dasan [26]. The amount of the residual char after the thermal decompositions reflects the amount of residual lignin and the ash. The result shows that the residual char reduces significantly compared to the raw OPF-VB biomass. This is attributable to the successful removal of the amorphous part of the extracted fibres [22].

3.2. X-Ray diffraction

The cellulose chain contains the crystalline (ordered) regions and the amorphous (disordered) regions [29]. **Table 3** shows the values of the fibre crystallinity of the OPF-VB fibres obtained from AP pretreatment systems. Crystallinity values are calculated by the formulae reported by Segal and team [31]. From **Table 3**, it is evident that there is an increase in the cellulose crystallinity as the alkaline peroxide concentrations increases from low AP concentrations to the medium AP concentrations. The percentage crystallinity dropped for fibres extracted at high AP concentrations.

The observed drop in the percentage crystallinity of the extracted fibre at high AP concentrations was as a result of a high amount of fines generated in the high AP concentration in the AP pretreatment system. This is in line with the observation reported by Segal and team [31] who similarly witnessed the loss of crystallinity upon excessive refining. Similarly, both Habibi and coworkers [32] and Lamaming and team [20] independently reported changes in crystallinity index of the respective substrate due to pretreatment. Trache and coworkers [33] reported that during refining, the intermolecular hydrogen bonds of cellulose are broken, causing the collapse of the crystal structure of the cellulose fibre. The x-ray diffraction patterns of the cellulosic fibres at different AP concentrations are shown in **Figure 3**, matching with the monoclinic sphenodic structure characteristic of cellulose 1 polymorph (which is unmodified form of natural cellulose) [34]. The similarity in the three X-ray diffraction patterns in **Figure 3** shows that the AP treatment at different concentrations maintains the natural cellulose 1 polymorphs structure of the biomass.

AP fibre Samples	Crystallinity
Low-AP	28.1%
Medium-AP	35.7%
High-AP	27.4%

Table 3. Crystallinity index of the OPF VB fibres.

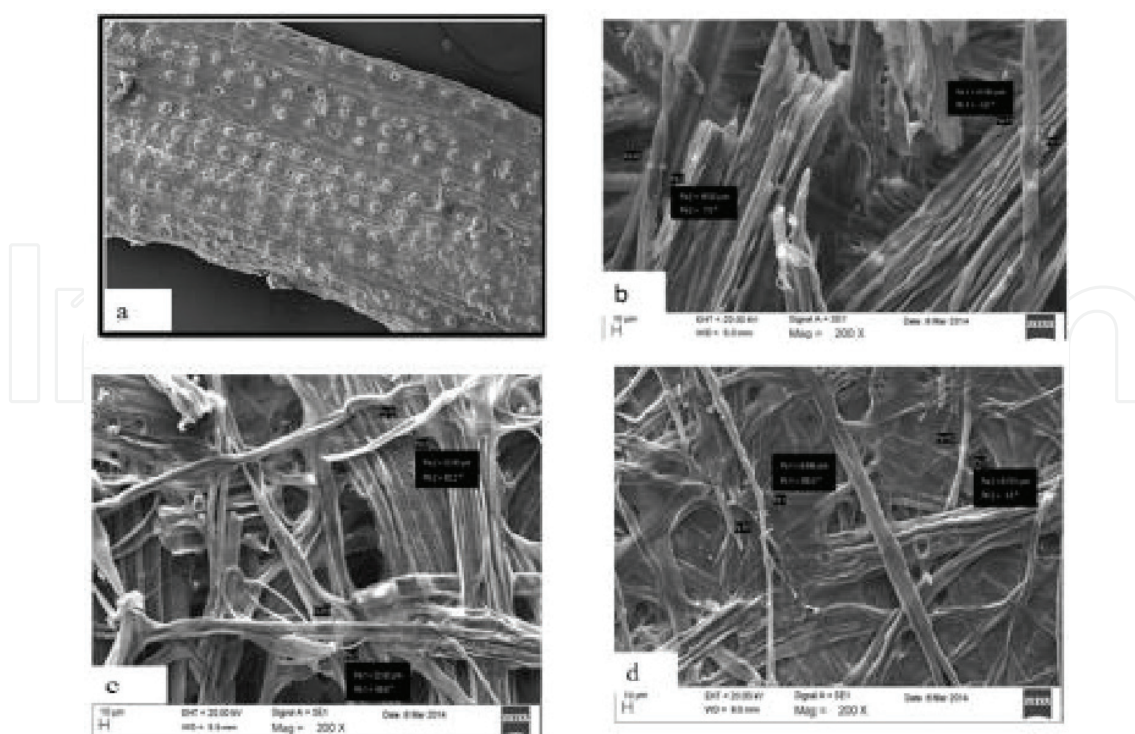


Figure 5. SEM images of (a) Raw OPF sample (b) AP treated fibre at low AP concentration (1.0 : 1.5), (c) AP treated fibre at Medium AP concentration (2.0 : 2.5) and (d) AP treated fibre at high AP concentration (4.0 : 5.0) paper web at different AP concentrations.

It is evident from **Figure 5** that the peaks at 22.20° , 22.40° , and 22.10° corresponding to A, B, and C, respectively are characteristic of native cellulose I polymorph [20, 31]. The X-ray diffraction technique revealed that the extracted cellulose fibres could be easily hydrolysed into the crystalline sample. Due to the softening effect of the treated fibres at high AP concentrations, the high fibrillations, cell wall delaminations aid the production of fibrillar fines at high AP concentrations; expose the crystalline cellulosic materials in OPF in a more profound manner.

The observed drop in the fibre crystallinity observed at high AP concentration treatment is attributable to the presence of certain threshold of fines content in the pulp. In a separate reports, Segal and coworkers [31] reported that fibre crystallinity could be lost by refining while Rafiee and Keshavarz [34] reported that fibre crystallinity could be lost due to high chemical treatment. This trend in the fibre crystallinity is in agreement with the report in the literatures [34]. The X-ray diffraction technique revealed that the extracted cellulose fibres could be easily hydrolysed into the crystalline sample.

3.3. Correlation between FTIR spectroscopy, DTG and XRD

The FTIR spectra of the raw and pulped fibres are shown in **Figure 4**, which shows the FTIR spectra of OPF fibre (A) Raw OPF vascular bundle fibres (B) OPF isolated at 1.5%:1.0%; H_2O_2 :NaOH AP concentrations (C) OPF isolated at 2.5%:2.0%; H_2O_2 :NaOH AP concentrations (D) OPF isolated at 5.0%:4.0%; H_2O_2 :NaOH AP concentrations. Analysis shows that despite the similarity, there are some shifts, disappearance and appearance of some signals of samples

after APMP process. This is apparent from the result in **Figure 4**. From the result, among the common bands were the 3400–3300 cm^{-1} region, which is attributed to the stretching of O-H groups, whereas those around 2900–2800 cm^{-1} were due to the stretching of C-H [20]. The appearance weak band at 2362–2135 cm^{-1} for the AP pretreated pulp at different concentrations is attributed to the C-C stretching vibration. This peak could be the result having phenyl ethynyl group that was generated during lignin dissolution [35] suggesting also lignin dissolution with AP treatment. The peak located at 1734 cm^{-1} in the raw OPF was assigned to the C=O stretching of the acetyl group in hemicellulose [37] or ester linkage of the carboxylic group in the ferulic and p-coumaric acids of either lignin or hemicelluloses [36]. The FTIR spectra reveal (as shown in Section 4) a shoulder at 1733 cm^{-1} for fibres generated via AP pretreatment system employing the medium and high AP concentrations. This characterizes the significant dissolution of hemicelluloses with the medium and high AP systems, in agreement with the DTG result in **Figure 4**. This observation is in contrast with the report by Ghazali and co-workers [17] that an increase in alkaline solution of hydrogen peroxide concentration caused an increase of lignin oxidation through a reduction in the aromatic rings. The peak at 1247 cm^{-1} could also be associated to the C=O stretching of the aryl group in lignin [35]. The shift of this peak coupled with weak absorbance was believed to be due to the reduction of lignin after the chemical treatments, while the weak signal indicates the presence of residual lignin [22]. The absorbance between 1426 and 1427 cm^{-1} for the raw OPF and OPF pulps is associated to the CH_2 symmetric bending [14]. The stretching of C=O and O-H can be observed as peaks around 1112–1114; 1054–1056 cm^{-1} and 897 cm^{-1} in all the pulp samples.

It is characteristic of glycosidic linkage between sugar unit samples [33], which are not present in the spectra of the raw samples. The absorbance peak at 1160–1164 cm^{-1} in the OPF raw sample and pulp is due to the anti-symmetrical deformation of the C-O-C band [36]. However the vibration peak at 897 cm^{-1} , which was absent in the raw sample, appear in the OPF pulp at the various concentrations. This was assigned to the glycosidic bonds, which are symmetric in polysaccharides [35].

3.4. Effect of alkaline peroxide pretreatment concentration on paper properties

Statistically, significant differences in the effects of AP concentration treatment level on the strength properties (tensile index, burst index and tear index) are also shown in **Table 1**. The ANOVA result shows that all the paper properties are significantly affected by the AP treatment except the burst index. The study showed that increase in the AP concentrations enhances the strength properties of the paper formed, which is in agreement with the trend already established with the paper apparent density. The impact of the high AP level on the fibrillation of OPF vascular bundle fibres become more apparently portrayed on the pulp web strength properties, and this stems from the higher probability of the lignin transformation to low molecular weight fragments and hence easily leached at high AP concentration treatment [17]. Furthermore high AP concentrations level produces higher fibrillation, which enhances fibre bonding and reduces fibre coarseness, thus leading to improved mechanical strength of the paper. Unlike the other strength properties, the ANOVA for AP treatment and time effect on AP strength properties (**Table 1**), the burst strength show no significant effect on the AP and time interaction effect. This observation is attributable to the fact that the bursting

strength of paper is a composite strength property that is affected by various other properties of the sheet, principally tensile strength and stretch [27]. The reason for the low burst index at low and medium AP concentrations is attributed to the presence of hemicellulose in the pulp fibre [27]. The extraordinary improvement in the burst index at high AP concentrations is attributed to the refining effect of well softened OPF biomass. The refining process is expected to increase the fibre swelling, hydration and extend of fibrillation degree, which result in an improved fibre flexibility and thus, bonding and strength of the paper. This enhances paper physical properties and burst index [22].

3.5. Surface Morphological Transformation of Papers from OPF

The paper samples obtained from the three AP pre-treatment concentrations (Low, Medium and High) were examined with Scanning Electron Microscope analysis (SEM) (**Figure 5**) to monitor the morphological transformation of the paper surface.

Figure 5 shows SEM images of (a) raw OPF vascular bundle and (b–d) handsheet surface corresponding to AP of (b) low; (c) medium; (d) high AP concentrations.

Overall as apparent in SEM analysis, the alkaline peroxide pretreatment has two effects on the fibre: In synergy with refining it increases the uniformity of paper arising from better interlocking of fibre and because of the softening effect of the alkaline peroxide chemical treatment, the treated samples displaced a greater degree of fibre collapsibility at high concentration. It exposes more cellulose of the biomass by modifying the lignin and leaching out the fragmented lignin.

4. Conclusion(s)

The study revealed that alkaline peroxide pretreatment of the OPF-VB at various AP concentrations produced a high quality pulp that could be attributed to easier fibre extraction from the biomass. Apart from the physical and mechanical properties, spectroscopic analyses confirm the ability of the pulping protocol to effectively remove non cellulose such as hemicelluloses, reduce the lignin content while realizing pulp and paper of high ISO optical brightness. The thermal analysis showed that the AP pretreated cellulose fibres have higher thermal stability than the raw sample, which made them suitable as biodegradable raw material in the polymer composite. The FTIR spectra is consistent also with the crystallinity values of the extracted cellulose fibres, which increased with an increase in the AP concentrations but decreased at high AP concentrations due to an increasingly generated fines materials, forming as a result of disruption of fibrous cell walls. The study showed that these extracted fibres will be useful in paper production and with further processing could be used as raw material for biodegradable composites with improved qualities.

Acknowledgements

The authors thankful to the Higher Institution Centre of Excellence (HiCoE) Ministry of Higher Education Malaysia Grant No. 6369107, the School of Industrial Technology Universiti Sains Malaysia and also the Federal institute of Industrial Research Oshodi Nigeria for their role in the successful completion of this book chapter.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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