Augmentation of EFB Fiber Web by Nano-Scale Fibrous Elements

Arniza Ghazali\textsuperscript{1,a}, Mohd Ridzuan Hafiz Mohd Zukeri\textsuperscript{1,b}, Wan Rosli Wan Daud\textsuperscript{1,c}, Baharin Azhari\textsuperscript{1,d}, Rushdan Ibrahim\textsuperscript{2,e}, Issam Ahmed Mohamed\textsuperscript{3,f}, Tanweer Ahmad\textsuperscript{1,g} and Ziya Ahmad Khan\textsuperscript{4,h}

\textsuperscript{1}Division of Bio-resource, Paper and Coatings Technology (BPC), School of Industrial Technology, Universiti Sains Malaysia, 11800 Penang, Malaysia
\textsuperscript{2}Forest Research Institute of Malaysia, 52109 Kepong, Selangor, Malaysia
\textsuperscript{3}Faculty of Science, Universiti Putra Malaysia, 43400 Serdang, Selangor
\textsuperscript{4}Department of Chemistry Faculty of Science North Jeddah Centre King Abdul Aziz University
Jeddah, Saudi Arabia

\textsuperscript{a}arniza@usm.my, \textsuperscript{b}m.ridzuanhafiz@yahoo.com, \textsuperscript{c}wanrosli@usm.my, \textsuperscript{d}baharin@usm.my, \textsuperscript{e}rushdan@frim.gov.my, \textsuperscript{f}issam@science.upm.edu.my, \textsuperscript{g}tanweerakhan@gmail.com, \textsuperscript{h}zakhan2@kau.edu.sa

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Abstract. Treatment of the abundant palm oil empty fruit bunches with alkaline peroxide chemicals and subsequent fibrillation at varying mechanical energies resulted in favourable morphological changes of the generated fibers. The produced fibrous mass composed of intensely fibrillated elements ranging from micro to nano-diameter fibrils. Nano fibrils and webs of nano-fibrils were factors contributing to the functionality of the fibrous mass as fibre web augmentation elements. Profound improvement in fiber network is particularly attributable to the ability of the collected elements to fill up inter-fiber gaps and this was attributable to the micro elements in the form of micro fines, segmented micro-fibrils and webs of nano-fibrils. The uniquely generated thin layers of nano-fibril webs (TN-webs), were found to increase fiber web density by gluing multiple layers of fibers, together. Having landed on the surface of micro-fiber web, these TN-webs were identified as responsible for the masking effects of the underlying micro-fibres. Under such condition, fibers were observed to ‘coalesce’, suggesting also an augmented fiber network as evident from the 130% increase in tensile index and a 450% enhancement in burst index of the resultant fiber web relative to those formed with the basic alkaline peroxide chemical-mechanical refining (CMR) synergy. This reveals a great promise to EFB for application as super-strong fibre-web materials such as packaging and specialty paper-based products.

Introduction

Commensurate with Malaysia’s long history of good environmental waste and effluent management [1], the once dross of the palm oil milling activities has been an acclaimed wealth factor, recently. Pulp-based packaging industry, for instance, announced a 63% savings on the capital for raw materials on switching to the use of fibrous mass from the oil palm empty fruit bunches (EFB) as the fibre source [2]. In fact, more applications from the research pipeline are projected for the sheer 20 mtpa EFB. Famed for wealth factor, the so-called ‘green gold’[2] continues to prompt works on its functionality through minimal processing and conversion to pollutant sorbents [3-5] to the practical possibility of improved bio-fuel production [6]. Beyond research, a small amount of EFB is already in use as medium-density fibreboard, mats, mattresses, cushions and light furniture. It is also compressed as briquettes [7] and incinerated for electricity generation [2, 7]. Destruction of EFB lignocelluloses matrix allows production of siliceous melt enabling glazing of ceramics and pottery [8]. On the contrasting consideration, EFB, having predominance of cellulose, lower level of lignin in comparison to most local wood and having unique fibre characteristics, show better viability as raw material for pulping and conversion to paper-based products [9-11] as compared to bio-energy [11] and glazing applications. Besides the
fibres as target yield, the waste constituting the loss in a typical fibre extraction process was also matchable to certain utilisation [12]. This, in turn, shifts the fibre industry closer to the zero-waste possibility.

From biomass utilization perspective, per hectare palm oil plantation could generate EFB pulp at least double the per annum pulp possibly harvested from the local rainforest. This corresponds to over 88 million trees-saving, on the assumption that all of the domestic EFB could be converted to pulp [7]. An economic way of doing this was attempted by applying an environmentally benign [8] and high-yield process concept of fibre extraction procedure, which was the breed of a alkaline peroxide mechanical pulping, APMP™ system reported by Cort and Bohn [13]. Within the system, the alkaline peroxide is an agent driving the swelling, softening and brightening of biomass and a subsequent mechanical fibrillation assist in the liberation of cellulosic fibrous mass. Being sulfur- and chlorine-free, the technique incorporates fiber extraction and bleaching in a single process or short segments of batch processes, thus, eliminating the need for a separate bleach plant, analogous to the acclaimed simplicity, flexibility and adaptability of the APMP™ system [13-17].

Early attempts of scrutinizing EFB responses to alkaline peroxide [8, 9, 18] observed the wide possibility of fibre web quality by adjustments of experimental parameters and machinery. The results of synergizing a fixed level of the alkaline peroxide with variable mechanical refining energies (in short, CMR synergy) in the process of extracting fibers from EFB is hereby discussed from the light of fiber web strength augmentation. The huge polarity in fiber morphology and fiber web strength foresees a favourable outcome for high-end utilization of EFB.

Method

Materials. The fibrous strands of EFB from Sabutek (Malaysia) Sdn. Bhd were washed and air-dried. The vascular bundle strands were ground to about 500 μm particles collected on 200-mesh screen (R200) using Retsch AS200 sieve and shaker. These particles were soaked in distilled water at 70°C for 30 minutes in water bath and pressed at 103 kPa pressure to be 50% extractive-free.

Fibre Extraction and Fibrillation. Alkaline Peroxide Pulping (APP) of EFB was carried out by submerging EFB in alkaline peroxide at 10-to-1 liquor-to-EBF for 30 minutes to reduce the chances of leachate redeposition [9] onto EFB surface. The alkaline peroxide containing 4% sodium hydroxide (NaOH) and 4.5% hydrogen peroxide (H₂O₂) was reacted with EFB for 30 minutes at 70°C and ambient pressure to soften and brighten the biomass. The AP-treated biomass was next refined using Sprout-Bauer 12" single disc refiner with 54.95 kWh/t specific refining energy for 4% pulp consistency and refining temperature of 33.5°C. The aforementioned condition is denoted as the basic alkaline peroxide chemical-mechanical fibrillation (CMR) synergy. Part of these fibres were subjected to further refining in the 1-20 kWh/mt energy range. CSF values were acquired in accordance to TAPPI Test Method T 227 om-99 [19], made into handsheet and examined for their web strength by selected mechanical testing (tensile, tear and burst) in T 227 om-99.

Microscopy and Fiber Analysis. Gold-coated fibre web and fibre smear were examined qualitatively using Carl Zeiss Leo Supra 50VP scanning electron microscope (SEM). Fibre dimensional characteristics and by-size fractions were acquired from Sherwood FAS-3000 Fiber Analysis System (USA), and this analysis was performed on pulp suspensions as recommended by the instrument manufacturer.

Results and Discussion

Dimensional Analysis of Fiber Fractions. Under the lowest possible alkaline peroxide chemical-mechanical refining (CMR) synergy, an APP process was reported as consisting of fibre bundles, vessel elements, fibers and fibrillated vessel elements [12]. Heightening of the CMR synergy by increasing the mechanical fibrillation energy (while keeping the alkaline peroxide at fixed level) resulted in further shearing and cutting of the fibrous mass and this is depicted on the CSF values in Table 1.
Table 1, Canadian Standard Freeness of EFB Fibres by Fibrillation Energies

<table>
<thead>
<tr>
<th>Web Name:</th>
<th>Fibrous Mass by Fibrillation Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 kWh/mt</td>
</tr>
<tr>
<td>CSF (ml)</td>
<td>(FM0) 495</td>
</tr>
<tr>
<td>Relative %</td>
<td>-25%</td>
</tr>
<tr>
<td>Relative to FM0</td>
<td>0%</td>
</tr>
</tbody>
</table>

NB: Basic CMR Synergy ≡ 0 kWh/t

From 1.7 kWh/mt to 17 kWh/mt, reduction in long-fibre counts is followed by an increment in the proportion of fines for a total of 139%, which corresponds to a gradual drop of 25%, 73%, 84% and 88% in the CSF relative to the native APP fibres (FM0, Table 1). This further reflects the aforementioned vast increase in fines contents and in turn, an increase in surface area for hydrogen bonding between water and fiber. Besides fines, internal and external fibrillation of fibres had increased exposure of the internal fibre structures and these also provide areas of contact with water, besides increasing the possibility of such entanglement as in Fig 1.

Fiber length of the fibrous mass decreased with an increase in fibrillation energy (Table 2) due to the anticipated severe shortening of fibers arising from continuous mechanical shearing force. Only meagre counts of long fiber constituted the fibres mass while a relatively more uniform count of medium, short and fines fiber were obtained. From handling perspective, the extremely low CSF value of FM4, therefore, increases the probability of water-fiber bonding and the resultant poor drainability and this could be a serious obstacle in papermaking line due to the tendency of fines to agglomerate and block the papermaking screen. These materials, however, may intrinsically improve paper web strength, analogous to the effects reported by Kamaluddin and team [12].

Table 2, Dimensional Fraction (%) of Fibres and Fines

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Fraction Name</th>
<th>Fibrous Mass by Dimensional Fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (µm)</td>
<td>Length (mm)</td>
<td>FM0</td>
</tr>
<tr>
<td>&lt; 3-60</td>
<td>&lt; 0.11</td>
<td>14.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+7%</td>
</tr>
<tr>
<td>3-60; 0.11-0.45</td>
<td>Short</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+19%</td>
</tr>
<tr>
<td>3-60</td>
<td>0.56-1.46</td>
<td>50.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.2%</td>
</tr>
<tr>
<td>3-60</td>
<td>1.57-7.17</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-42%</td>
</tr>
</tbody>
</table>

Fibre length ranging from 0.125-0.250 mm is ideal [20] for intense fiber-to-fiber bonding. In this regard, long structures such as split vessels are liable for the interruption of fiber-fiber bonding due to the risk of entanglement or agglomeration, which adds the count of over-sized structures [20]. The favoured hydrogen bonding of the obtained pulp results in good mechanical strengths (Fig. 2). The more often fluffy (Fig 1a), rather than linear structures (Fig. 1c) provide bonding sites besides by filling snugly into the fibre web micro-voids.
Mechanical Properties. A maximum of 5 kWh/mt mechanical fibrillation produced the desired external fibrillation of the commonly encountered fibre bundles as portrayed by FM1 and FM2. Predominance of medium-size fibrous mass (Table 2) resulted in the increasing tensile and burst indices (Fig. 2) due to the availability of fibres offering good possibility of hydrogen bonding. This is also rendered by the high relative abundance of the long fibres.

Shortening of fibrillated vessel elements resulted in gradual predominance of short-fibers starting from FM3 where 8.3 kWh/mt energy was applied. These short fibres offered no more hydrogen bonding sites per fiber and show no further increase in tensile strength of the fiber network (Fig. 2a) as web’s ability to withstand the pulling force till the point of brittle failure depend not only on fibre bonding, but also fibre length and, to a less extent, fiber strength. The web formed by bonding promoted by the shorter fibrous mass, moreover, showed resistance to burst impact with an increase in fibrillation energy (Fig 2b). This is attributable to the positive gluing effects of fibrils and thin fibril webs (Fig. 3b), which had ultimately diminished micro-void and web porosity. This extensive adhesion between fines-fiber and fines-fines leading to high fiber packing is portrayed in Fig. 4c. Uniquely, the generated fines serve more as natural filler of micro-voids, which is typical of alkaline peroxide EFB fibre network. These fillers reduce the possibility of fibers being pulled out of the paper plane, resist air flow and thus, enhancing pulp network resistance to burst impact.

Fibre Web Microscopy. With the common mass of 200 µm to 1000 µm fibres (Table 2) in FM0 less of fines flogs are winessed in Fig 3a (right) as compared to the more glaring evidence of submicron fibrils dangling on the fibrillated fibers (Fig 3b, right). The transition in the extent of fibrillation of the fibre surface resulted in the dodgy appearance of fibre web by the intensely fibrillated fibers (Fig 3b cf. Fig. 3a). Besides the dodging effect, the web of fibrils had also rendered the aforesaid gluing effect, evident from the enhanced mechanical strength of the fibrillated-fibre web. The friction forces of fibrillation process had also led to the formation of an extremely thin fibrous sheets (Fig. 3c). Higher magnification of these sheets shows vast amount of threads of nano-fibrils (Fig. 3c – far right). Apart from filling up internal voids, these are also likely
to land on the surface of the fibre web, giving the coalescence appearance. Specifically in the case of FM4, well-defined fibers are evidently masked on the web surface (Fig. 3c – far left). Apart from that, the nano-fibrous construction is also believed to impose the overall translucence effect of the associated fiber web sheets. In their presence, there are higher chances of nano-voids being filled up, resulting in an apparently condensed fibre web and thus, high sheet density.

Fig. 3. Fiber web surface and the associated fiber suspension for (a) basic (0 kWh/mt) and (b) 1.7 kWh/mt and (c) 17 kWh/mt CMR synergies. An additional micrograph on the right for (c) shows evidence of nanofibre network.

**Conclusion**

The applied mechanical fibrillation energies offered a huge polarity of pulp qualities, apparent from the 130% and 450% possible increase in tensile and burst indices, comparing the web of fibers from basic CMR synergy to the applied maximum fibrillation energy. This is attributable to the tremendous increase in bonding sites and filling of voids by sub-micron fibers and thin layers of nano-fibril webs (TN-webs). The overall findings demonstrate the possible fiber web augmentation by nano-web elements by their intrinsic gluing and packing properties. Although moderate in compensating with the sacrificed fiber strength and length, these elements manifest more possibility of exploiting EFB in higher end pulp-based products development.

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References


