Micro/Nano Papers from Bagasse Pulp Reinforced by Bacterial Cellulose Nanofibers

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Abstract. The aim of this research was to use bacterial cellulose (BC) as a biodegradable reinforcing agent in bagasse (BG) paper sheets. BC was cultured by Komagataeibacter nataicola and defibrillated into isolated nanofibers by using microfluidizer. Micro/Nano (BG/BC) papers were prepared by adding 0.5 and 5 wt% BC in BG pulp and then the paper sheets were fabricated by compression molding. The morphology, physical and tensile properties of the prepared sheets were studied. It was found that adding BC increased the density of BG sheets while their porosity was decreased. SEM images confirmed that BC filled gaps and bridged between BG fibers leading to a raise in fiber bonding. With increasing BC content, the mechanical properties of paper sheets were clearly improved. The addition of 5 wt% BC significantly enhanced the tensile strength and elongation at break of the reinforced sheets by 47% and 117%, respectively. Furthermore, the tensile index and breaking length of the BG sheets were increased for approximately 35%.

1. Introduction

The production of specialty paper products such as high-strength papers requires an additive or strengthen binder to enhance their properties. Bacterial cellulose (BC) has been investigated as a paper binder because it has several benefits over plant cellulose such as high purity, high tensile strength and high crystallinity [1, 2]. In previous works, BC has been successfully used as a paper additive in bleached spruce sulfite pulp for the high-strength functionalized paper sheets as well as in softwood sheets [2, 3]. Besides wood, non-wood resources such as rice straw, bamboo and bagasse are the available fiber sources and has potential to produce suitable pulps for various applications [4]. Bagasse (BG), the fibrous residue that remains after sugarcane stalks are crushed to extract their juice, is one of the largest agriculture residues in the world and currently also used in the manufacture of pulp. This work aims to study the feasibility of using defibrillated BC as a reinforcement in the BG paper sheets. The Micro/Nano (BG/BC) papers were fabricated and characterized in term of their morphology, physical and mechanical properties.

2. Experimental

2.1. Preparation of bacterial cellulose nanofibers

Bacterial cellulose (BC) was cultivated by Komagataeibacter nataicola in the medium composed of sucrose 50 g, yeast extract 5 g, KH₂PO₄ 3 g and MgSO₄.7 H₂O 0.05 g dissolved in 1 L of water. The
produced BC was harvested to prepare BC suspension in water at a concentration of 0.5% for 400 mL and then homogenized using a microfluidizer (M-110P, Microfluidics) equipped with the Y-type chamber (size of 87 µm) at 25,000 psi for 10 cycles.

2.2. Preparation of bagasse pulp
Bagasse (BG) was obtained from Biodegradable Packaging for Environment Public Co., Ltd (BPE), Thailand. BG paper was torn into small pieces and soaked in tap water overnight. The soaked BG papers were defibrillated by using a kitchen blender (House Worth, HW-BDC2PC) at speed of 15,000 rpm for 5 min. The BG slurry was screened on the metal mesh sieves with 1 mm slits and 0.074 mm. The pulp remained on the 1 mm slit sieve was rejected. The screened pulp on the 0.074 mm slit sieve was collected and then adjusted to 2% pulp consistency.

2.3. Preparation of micro/nano (BG/BC) papers
To prepare the Micro/Nano paper sheets, the mixtures of BG and BC slurries were prepared. The BC was added into the BG slurry with the varied contents of 0, 0.5, 5 wt% and then mixed for 1 min by hand. The well-dispersed mixture was pre-formed into a wet sheet between two metal meshes (no.400) and water was then partially removed out. After that, the wet sheet was hot-pressed for 5 min at 105°C under pressure of 159 kPa to obtain the dried paper sheet.

2.4. Characterization

2.4.1. Morphology. Scanning electron microscope (SEM) (LEO/1450 VP) was used to observe the characteristic of BG fibers and the morphology of prepared sheet surfaces with an accelerating potential of 10 kV. Before observation, BG fibers was diluted in water and adjusted into 0.2% pulp consistency, then dropped onto a transparent sheet and placed in a desiccator until dried. The dimension of BG fibers was measured and averaged from 50 fibers. For the paper sheets, they were cut into the size of 5 mm × 5 mm and coated with carbon by sputtering before examination. On the other hand, the morphological analysis of BC was carried out using a transmission electron microscope (TEM) (Hitachi Model HT7700) with an acceleration voltage of 80 kV. The BC suspension was diluted to 0.001% consistency and dropped on a copper grid with formvar film support. All samples were then dyed with 2% uranyl acetate (UA) for 5 min and kept overnight before observation. The dimension of BC was measured and averaged from 10 fibers.

2.4.2. Physical properties. To assess the density of the paper sheets, they were cut into rectangular specimens with the dimension of 10 mm × 50 mm. Then the thickness, width and length of each specimen were carefully measured by using a digital Vernier caliper. Next, the volume \((cm^3)\) of each specimen was calculated from its measured dimension. Also, the weight \((g)\) of each specimen was recorded by a 4-digit balance. The density of each specimen was calculated by using the following equation:

\[
D = \frac{M}{V}
\]

where \(D\) is density of specimen \((g/cm^3)\), \(M\) is weight \((g)\) and \(V\) is volume \((cm^3)\).

The weight per unit area of paper sheets was defined as grammage (according to TAPPI T410). The grammage was calculated from the ratio of the mass \((g)\) to the area of sheets \((m^2)\). The porosity of each specimen was calculated by using the following equation:

\[
\text{% Porosity} = \left(1 - \frac{\text{density of sheet}}{\text{density of cellulose}}\right) \times 100
\]

where the density of cellulose is 1.53 g/cm³.
2.4.3. Tensile test. To prepare the test specimens, the paper sheets were cut into the size of 10 mm × 50 mm with a gauge length of 30 mm. Then, the specimens were pre-conditioned at 50% RH and 25°C overnight before testing. The tensile test was performed according to TAPPI T494 by using a universal testing machine (Instron Model 5566) equipped with 1 kN load cell. The constant crosshead speed of 15 mm/min and pre-load at 1 N were set before starting the test. The tensile index, tensile strength, breaking length and Young’s modulus of the prepared paper sheets were evaluated subsequently from the test results. The reported values of their tensile properties were averaged from 5 specimens.

3. Results and Discussion

3.1. Morphology

Figure 1A shows the SEM micrograph of BG fibers with their dimensions in microscale level (see also Table 1). On the other hand, after passing through the microfluidizer for 10 cycles, BC network was turned into individual nanofibers. However, some were still together and remained partially network-like (Figure 1B) [5]. From Table 1, it can be clearly noticed that the BG fibers have a considerably low aspect ratio when compared to that of the BC nanofibers.

![Figure 1](image1.png)

**Figure 1.** SEM image of bagasse fibers (A) and TEM image of bacterial cellulose (B) after 10 passes through the microfluidizer.

|                  | Type of fiber | Length (L)       | Width (D)       | Aspect ratio (L/D) |
|------------------|---------------|------------------|-----------------|--------------------|
|                  | BG            | 274.8 ± 105.9 µm | 11.7 ± 4.9 µm   | 29                 |
|                  | BC            | 10.5 ± 2.7 µm    | 3.5 ± 2.0 nm    | 336                |

![Table 1](image2.png)

**Table 1.** Size of bagasse microfibers (BG) and bacterial cellulose (BC) nanofibers

![Figure 2](image3.png)

**Figure 2.** SEM images of pure bagasse sheet (A) and bagasse sheet containing 0.5% (B), 5% (C) of bacterial cellulose at 1000x magnification.

The SEM images of the surfaces of the pure BG sheet and BG sheets contained BC are shown in figure 2A and 2B-C, respectively. It was revealed that the added BC nanofibers filled the gaps between BG microfibers and smoothen the sheet surfaces (figure 2B-C).
3.2. Properties of the paper sheets

The plot of the density and porosity of the prepared paper sheets is shown in figure 3. It was found that the density of the paper sheets was increased with increasing BC content, but their porosity was steadily decreased. It was likely due to BC filling the gaps in the BG sheet structures and, hence, the less porous sheets with higher density were obtained as a result [6]. In general, the density and porosity of papers are highly related to their mechanical properties. It is supposed that the higher density papers have greater fibers packing, which could lead to an enhancement in the mechanical properties of paper sheets [7].

![Figure 3](image3.png)

**Figure 3.** Density and porosity of the pure BG, and BG with 0.5% and 5% BC paper sheets.

From the tensile results, the addition of BC improved tensile properties of the BG paper sheets as shown in Figure 4 and 5. Because the presence of BC increased the bonding ability within the sheet structures and they closed the gaps by bridging between these BG fibers [3,6]. For the BG sheet with only 0.5% BC, its tensile index and breaking length were increased approximately 10%. When increasing BC content to 5%, the tensile index and breaking length of the sheet were further enhanced up to 35% increment (figure 4). In the previous work, T. Tabarsa et al. studied the use of BC to improve properties of the softwood pulp (SP). The 5% BC reinforced SP sheet showed an increase in tensile index of 12% [6]. C. Campano et al. also reported that the recycled pulp sheet with 6% BC addition presented an increase in its tensile index around 22% [8]. From the comparison with these former works, it was indicated that the present defibrillated BC fibers showed a greater reinforcing efficiency than unmodified or untreated BC.

![Figure 4](image4.png)

**Figure 4.** Reinforcing effect of BC nanofibers on tensile index and breaking length of the BG sheets.
In addition, the 5% BC added sheet (BG-BC 5%) showed the significant increase in its tensile strength and elongation at break (47% and 117%, respectively) when compared to those of the pure sheet (BG-BC0) (figure 5). The overall results also confirmed that the defibrillated BC nanofibers were able to effectively improve all tensile properties including tensile index, breaking length, tensile strength, and elongation at break of the BG paper sheets.

4. Conclusion
The defibrillated BC nanofibers were prepared by using a microfluidizer. Different contents (0.5 and 5 wt%) of BC were incorporated in the BG pulp and then fabricated into the paper sheets by using a compression molding. As the dosage of BC in the BG sheets was increased, their density was raised but porosity was reduced because BC was found to fill in the gaps and bridge between BG fibers as revealed by SEM images. With 5 wt% BC addition, the tensile index and breaking length of the BG sheet were improved by approximately 35%. Its tensile strength and elongation at break were also greatly enhanced by 47% and 117%, respectively. The potential reason for these improvements attributes to an increase in inter-fiber bonding within the BG sheet structure due to the presence of BC nanofibers. Thus, it can conclude that the defibrillated BC is an effective choice and feasible to use for developing papers, specialty papers and other related products.

5. References
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