Original Article
Journal of Biosystems Engineering
J. Biosyst. Eng. 43(4):362-368. (2018. 12)
https://doi.org/10.5307/JBE.2018.43.4.362
eISSN : 2234-1862
pISSN : 1738-1266

# Performance Evaluation of Batch Pulp Digester using By-product (Sheath) from Bamboo Laminate Production

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Received: July 27th, 2016; Revised: May 27th, 2018; Accepted: August 24th, 2018

**Abstract**

**Purpose:** Self-sufficiency in paper production is desired in Nigeria. This study was aimed at evaluating the performance of a locally fabricated batch pulp digester. **Methods:** The pulp yields of sheaths generated as waste in the production of bamboo (*Bambusa vulgaris*) laminates were determined at different liquor concentrations and treatment time after preliminary experiments to ascertain the conditions under which the sheath started to pulp. Moreover, the optimum pulping conditions and fiber characteristics were determined and estimated, respectively, to ascertain the pulp fiber suitability for paper production. **Results:** An optimum pulp yield of 65.1% was obtained at 50% NaOH and 25% $Na_2S$ liquor concentration (w/w) when the cooking time was 4 h. The results of fiber characterization of the pulp indicated an average fiber length of 2.19 mm with a low Runkel ratio of 1.63, both of which signify the suitability of the pulp for medium quality paper production. **Conclusions:** Softwood pulp can be blended with the fibers to improve the strength of the produced paper; further investigation should be carried out to use other non-woody plants for pulp and papermaking.

**Keywords:** *Bambusa vulgaris*, Fiber, Papermaking, Pulp digester, Pulp yield

## Introduction

Paper is a natural product manufactured from various materials such as straws, cotton, hemp, jute, bagasse and, most commonly, wood. The paper products are widely used across various fields. As reported by Wayman (1973), the total pulp, paper, and paperboard production in Nigeria in 2007 was estimated to be 0.019 million metric tons. The quantitative need of pulpwood for papermaking is expected to increase to approximately 2,719,900 $m^3$ before the end of 2020 (Olorunnisola, 2013). Therefore, to supplement pulpwood fibers, attempts are being undertaken to find other sources of high-grade fibers for paper production.

Pulp can be produced through delignification of cellulose-containing plants. This process can be achieved by utilizing mechanical methods, in which fibers are shredded apart through attrition; chemical processes, in which the lignin bound to the fibers is completely dissolved by cooking the woodchips in suitable chemicals; or combination of both mechanical and chemical processes (Abreu, 2000). The foremost method used in pulp mills is the chemical pulping, which involves the pressure cooking of a mixture of woodchips and chemicals in a specialized reactor called a pulp digester. The quantity and quality of pulp fibers produced in a digester significantly depend on factors such as cooking temperature, pulping pressure, chemical concentration, and cooking time, all of which affect the penetration and diffusion of the pulping chemicals into the interior of the pulp material This chemical pulping method can either be carried out under acidic condition (sulfite pulping) or alkaline condition (sulfate or Kraft pulping) (Chandra, 1998).

Although wood is still the major source of fiber in pulp and paper industries, efforts have been undertaken to

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investigate the potential of utilizing non-woody plants such as herbs, vines, and bamboo for papermaking. Research of potential alternatives to wood is particularly crucial as it would lead to development of ways to reduce forest depletion caused by over-exploitation of trees for building and construction purposes (Chandra, 1998). In this regard, a vast species of bamboo (*Bambusa vulgaris*) has been reportedly used in paper production (Irvine, 1961; Wayman, 1973). Bamboo offers advantages over wood as a raw material in papermaking—it grows rapidly, readily available for use within a few years, and easily coppices. Moreover, the amount of cellulose material from bamboo is estimated to be 6–7 times more than that from other trees. (Lessard and Chouinard, 1980).

The sulfate (Kraft) process is considered more suitable for pulping bamboo than the acid sulfite process (Ogunsile and Uwajeh, 2009). The structure of bamboo differs from wood; bamboo has solid nodes and hollow internodes at regular intervals. The solid nodes have a high density and silica content, which causes considerable difficulties and expenses in chipping and pulping (Singh and Naithani, 2008). An easier way to make paper from bamboo is to use the sheaths (the outer coverings), whose texture is similar to that of a dry corn husk. These sheaths are usually generated as waste during the production of laminates from bamboo culms, and Zhan et al. (2017) has provided information on their anatomical and chemical properties. This study is, therefore, aimed at pulping the sheaths from bamboo culms by using a batch pulp digester in order to ascertain its potential as a source of raw material in pulp and paper industries in Nigeria.

# Materials and Methods

## Materials

The bamboo culms used for the study were collected from the river banks of Baptist Church premises in the University of Ibadan, Nigeria. The culms were manually sliced into strips and processed into laminates through planing, generating their outer coverings (sheaths) as waste. The sheaths were gathered and oven-dried until the moisture content reached about 5% (wet basis). They were later screened to exclude undersized and oversized sheaths; 100–150 mm long, 5–10 mm wide, and about 2 mm thick sheaths were selected for pulping (Fig. 1). The selected sheaths were then packed and stored in polythene bags at room temperature of 20-25℃. The pulping liquor used for the Kraft pulping process was prepared from a mixture of sodium hydroxide (NaOH) and sodium sulfide ($Na_2S$).

## Determination of pulp yield at varying conditions

The oven-dried sheaths were pulped at varying concentrations of pulping liquor (aqueous solution of NaOH and $Na_2S$) and treatment time. The proportions of each chemical were varied in accordance with the weight of the pulped sheaths. The w/w ratio of NaOH/$Na_2S$ pulping liquor solution is maintained as 2/1 for all pulping experiments (Table 1).

**Figure 1.** Bamboo sheaths used for pulping.

**Table 1.** Varied conditions of pulping at different concentration of pulping liquor and time of treatment

| Concentration of Pulping Liquor (%, w/w) NaOH/$Na_2S$ | Treatment Time (h) |
|---|---|
| 25/12.5 | 3 |
| | 4 |
| | 5 |
| 50/25 | 3 |
| | 4 |
| | 5 |
| 75/37.5 | 3 |
| | 4 |
| | 5 |

The sheaths were weighed and pulped in the pulp digester having 20-l capacity in batches. The pulping process (MacLeod, 2007; Omoniyi and Onilude, 2013) was carried out in three stages:

(i) *Pre-steaming stage* at a temperature of 100℃ for 15 min (to open the pores and voids in the sheaths for impregnation of the pulping liquor),

(ii) *Liquor impregnation stage* at a maximum temperature of 130℃ for 45 min (to allow the chemical solution to penetrate deep into the voids and lumens of the Bamboo cells), and

(iii) *Cooking stage* at a maximum temperature of 17 0℃ for the required treatment times of 3, 4, and 5 h for all pulping experiments. In addition, the pulping pressure was raised to and maintained at 0.6MPa throughout the experiments.

The pulping conditions—treatment time and concentration of pulping liquor—were varied throughout the pulping experiments to determine the effect of each condition on the pulp yield. The treatment times were varied at 1 h intervals (3, 4, and 5 h). Each experiment at each condition of pulping liquor concentration and treatment time was replicated three times (total of 27 experiments) to obtain the average pulp yield at each condition (Table 1). The pulping experimental conditions (Bakare, 2008; Omoniyi and Onilude, 2013) were as follows:

Bamboo to pulping liquor ratio (w/w) = 1:6

Sulphidity ($\frac{Na_2S}{Na_2S + NaOH} \times 100\%$) = 33.3

Causticity ($\frac{NaOH}{Na_2S + NaOH} \times 100\%$) = 66.7

Rise to Temperature (minutes) = 90

Maximum Temperature (°C) = 170

At the end of each pulping experiment, the digester was turned off and allowed to cool. The pulped contents were collected, washed to get rid of the spent liquor, and diluted with 10 l water. After separation of the rejects, the obtained pulp was drained and weighed to determine the percentage pulp yield. In addition, statistical analyses by analysis of variance and Duncan's multiple range test were carried out using SPSS 16.0 (SPSS Inc., Chicago, USA) to determine the significant difference ($\alpha$=0.05) in pulp yield at different conditions of pulping.

## Determination of the pulp's fiber characteristics

Samples of the pulp produced at the optimum condition (highest pulp yield with minimum liquor concentration and treatment time) were prepared on a clean slide and mounted on a microscope slide table. Twenty five sample fiber cells were randomly selected, viewed, and measured under a Carl Zeiss photomicroscope using a total magnification of X400 (X10 magnification of ocular lens and X40 magnification of objective lens) to determine the fiber length, fiber diameter, and lumen width (void area or empty space within the wood cell reserved for the longitudinal passage of fluid and other materials) measured at different points along the base, middle, and top of the sample fibers by using the method reported by Oluwadare and Egbewole (2008). Other morphological indices such as cell wall thickness, coefficient of flexibility, Runkel ratio, and felting power that affect paper quality were estimated as follows (DeBell et al., 1998):

i. *Cell wall thickness*: This indicates how thick the walls of the fibers are. This parameter has an impact on the strength of the final produced paper.

$$\text{Cell wall thickness} = \frac{\text{fiber diameter} - \text{lumen width}}{2}$$

ii. *Coefficient of flexibility*: This is a major parameter responsible for burst and tensile strength as well as development of the paper properties that affect printing.

$$\text{Coefficient of flexibility} = \frac{\text{lumen width}}{\text{fiber diameter}} \times 100$$

iii. *Runkel ratio*: This is the measure of the amount of cell wall thickness with respect to the cavity of the lumen of the fiber. Generally, the suitability of a material for pulp and paper is significantly determined by its Runkel ratio. Lower the ratio, better is the material for papermaking.

$$\text{Runkel ratio} = \frac{2 \times \text{Cell wall thickness}}{\text{Lumen width}}$$

iv. *Felting power*: Also referred as the slenderness ratio, it is an important index for estimating pulp quality of fibers.

$$\text{Felting power} = \frac{\text{Fiber length}}{\text{Fiber diameter}}$$

### Examination of the microstructure of the fibers

Sample fibers from the pulp at the 50% NaOH/25% $Na_2S$ liquor concentration and 4 and 5 h treatment times were thoroughly rinsed with distilled water in a conical flask. They were dipped into the safranin solution and left for 3 min. The specimens at each treatment time were rinsed again with distilled water and stained with methyl blue and alcian blue dyes for easy microscopic examination. After successive dehydration with ethanol, the specimens were properly mounted on separate slides using a drop of glycerol before being viewed under the Carl Zeiss photomicroscope with X400 magnification.

The schematic representation of the process summary is shown in Figure 2.

## Results and Discussion

### Results of pulp yield at varying conditions

Pulp yields were measured at varying liquor concentrations and treatment times to determine the optimum conditions. The pulping conditions that required minimum treatment time and minimum liquor concentration that produced the highest yield gave the optimum conditions of pulping. The average pulp yields under various conditions are shown in Figure 3.

Figure 3 showed that at any liquor concentration, the pulp yield increases with increasing treatment times although the percentage increase recorded between 3–4 h was higher than that between 4–5 h. This is an indication that lignin loss beyond 4 h of cooking is minimal. Moreover, at any treatment time, increasing the liquor concentrations increases the pulp yield, which indicated that more delignification was achieved at higher concentrations although more damage occurred on the fibers in the pulp produced at the 75% NaOH/ 37.5% $Na_2S$ liquor concentration as observed under the microscope. The maximum average pulp yield (66.66%) was recorded at the 50% NaOH/25% $Na_2S$ liquor concentration at the end of 5 h of cooking. The results of the statistical analyses of the pulp yields with liquor concentrations and treatment times are shown in Tables 2, 3, and 4.

From the results of the analysis of variance and Duncan's multiple range test, there is no significant difference between pulp yields at 4 and 5 h as well as between pulp yields at the 50% NaOH/25% $Na_2S$ and 75% NaOH/37.5% $Na_2S$ liquor concentrations. Thus, the performance of the pulp digester was based on the optimum pulping conditions at the 50% NaOH/25% $Na_2S$ liquor concentration and 4 h treatment time that gave a pulp yield of 65.1%.

### Result of fiber characteristics of the pulp produced at optimum condition

The morphological indices obtained for the samples compared to similar results from other parts of the world

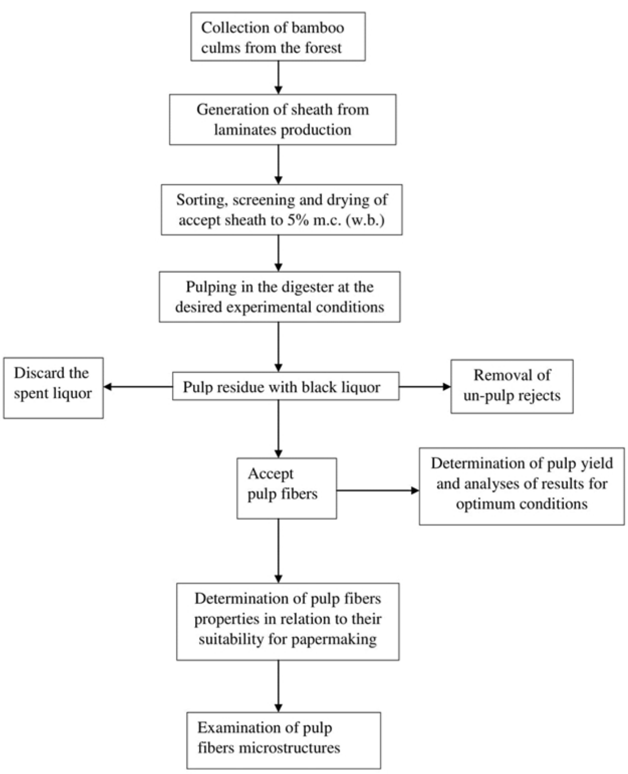


**Figure 2.** Schematic diagram of the summary of the process flow.

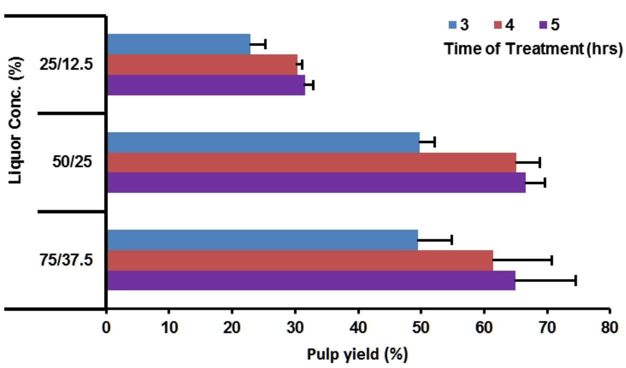


**Figure 3.** Pulp yields (%) at varying concentration of liquor and treatment time.

**Table 2.** Analysis of variance of pulp yield at varying treatment times and liquor concentrations

| Source | DF | Squares | Mean Square | F-Value | Pr> F |
|---|---|---|---|---|---|
| Model | 8 | 6961.18 | 870.15 | 32.20 | < 0.0001 |
| Error | 18 | 486.39 | 27.02 | | |
| Corrected Total | 26 | 7447.56 | | | |
| Source | DF | Type III SS | Mean Square | F Value | Pr> F |
| Liquor Conc. (L) | 2 | 5908.29 | 2954.15 | 109.33 | < 0.0001 |
| Treatment times (T) | 2 | 979.37 | 489.68 | 18.12 | < 0.0001 |
| L×T | 4 | 73.52 | 18.38 | 0.68 | 0.6146 |

**Table 3.** Duncan's multiple range test of pulp yield and concentration of liquor

| Mean | No. of Expt. | Liquor Conc. (%) |
|---|---|---|
| $28.3^b$ | 9 | 25/12.5 |
| $60.5^a$ | 9 | 50/25 |
| $58.7^a$ | 9 | 75/37.5 |

Means with the same letter are not significantly different.

**Table 4.** Duncan's multiple range test for pulp yield and treatment time

| Mean | No. of Expt. | Treatment Time (h) |
|---|---|---|
| $40.7^b$ | 9 | 3 |
| $52.4^a$ | 9 | 4 |
| $54.4^a$ | 9 | 5 |

Means with the same letter are not significantly different.

**Table 5.** Mean values of morphological indices of bamboo at different locations

| Fiber parameters | Tested Sample | *Ghana | *Phillipine | *India |
|---|---|---|---|---|
| Fiber length (mm) | **2.19** | 2.65 | 2.33 | 2.02 |
| Fiber diameter (μm) | **22.82** | 14.60 | 17.00 | 15.06 |
| Lumen width (μm) | **9.72** | 9.65 | 4.00 | 3.98 |
| Cell wall thickness (μm) | **6.54** | 4.95 | 7.00 | 5.52 |
| Runkel ratio | **1.63** | 1.03 | 3.50 | 2.77 |
| Coefficient of flexibility (μm) | **42.11** | 66.10 | 23.00 | 26.42 |
| Felting power (μm) | **100.87** | 182.00 | 137.00 | 134.00 |

*Source: Lessard and Chouinard, 1980.

are shown in Table 5.

As shown in Table 5, the result of the morphological indices compared favorably with those reported in literature. The sample fiber length of 2.19 mm falls within the medium fiber range of 1.0–2.4 mm (Federal Ministry of Science and Technology, 2003). This indicates its suitability for the production of medium quality papers, such as sanitary tissue papers, newsprints, and printing papers. The felting power of 100.9 μm of the sample fiber is the lowest when compared with other results, indicating relatively reduced pulp quality. This result might have been due to the excessive mechanical attrition during the slicing and peeling of the bamboo into sheaths. The flexibility coefficient of 42.1 μm of the sample fiber is lower than the value from Ghana but higher than those from Philippine and India. This suggests that the fibers can be utilized for producing bulk paper with moderate strength properties (Ververis et al., 2004). The low Runkel ratio compared to the results from other countries indicates the overall suitability of the pulp for commercial papermaking.

## Microstructure of the Produced Pulp

At the 50% NaOH/25% $Na_2S$ liquor concentration, the microstructures of the fibers in the pulp at 4 and 5 h treatment times are shown in Figures 3 and 4, respectively. The fibers after 4 h treatment time (Fig. 4) were relatively long with slight damage to their cell walls; this may suggest that good fiber formation occurs at 4 h treatment time, resulting in good quality of the final paper product. In Figure 5, the fibers appear severely damaged (black dots around some individual fibers at the top and bottom right corner); this suggests possible impairment resulting in the degraded quality of the final paper product.

# Conclusions

From the result of this experiment, it can be concluded that the pulp yield of the sheaths from bamboo culms increases with increase in both the treatment times and liquor concentrations. The optimum conditions were

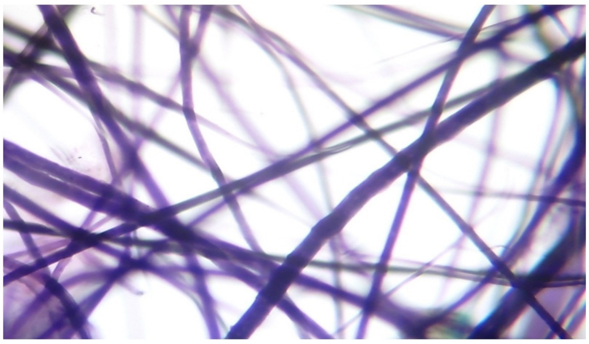

**Figure 4.** Microstructure of bamboo fibers at 50% NaOH/25% $Na_2S$ liquor concentration and 4 h treatment period.

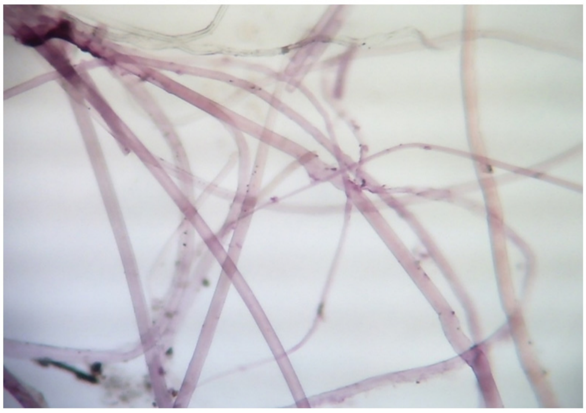

**Figure 5.** Microstructure of bamboo fibers at 50% NaOH/25% $Na_2S$ liquor concentration and 5 h treatment time.

determined to be the 50%NaOH/25%$Na_2S$ liquor concentration and 4 h treatment time at which the pulp yield was 65.1%. The highest pulp yield of 66.7% was recorded at the 50% NaOH and 25% $Na_2S$ liquor concentration and 5 h treatment time, at which the fibers were severely damaged. The fibers at optimum conditions had moderate quality and good fiber formation, suggesting their suitability for the production of writing, printing, and wrapping papers. However, pulp from softwood tree species can be blended with the fibers to improve the strength of the produced paper. Further studies should be carried out with other non-woody plants and shrubs to determine their suitability for pulp and paper production in Nigeria.

## Conflict of Interest

The authors have no conflicting financial or other interests.

## Acknowledgements

The authors would like to thank 2010/2011 M.Sc. students of the Department of Agricultural and Environmental Engineering (Wood Products Engineering option) for funding the experiments. The author is grateful to Mr. Alao, Department of Wood Anatomy, Forestry Research Institute of Nigeria (FRIN), Ibadan, for his invaluable assistance.

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