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Pulping Yield and Mechanical Properties of Unbeaten Bamboo Paper

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ABSTRACT

One way to minimize emissions of greenhouse gases that contribute to climate change is to reduce the use of wood as the main material for pulp and paper production. Therefore, non-woody plants such as bamboo can be alternatives as raw materials for pulp and paper. This study aims to determine the effect of the different bamboo species and age on the bamboo pulping yield and bamboo mechanical paper properties. *Bambusa vulgaris, Gigantochloa levis*, and *Gigantochloa scortechinii* bamboo species or locally known as *Aur, Beting*, and *Semantan* bamboo at the age of 1, 3, and 5-year old, were pulped using Soda-Anthraquinone (AQ) pulping. No beating process was conducted to all the papermaking processes to evaluate the basic mechanical properties of the bamboo paper. Pulping yield ranged from 35.7 to 51.7% at different bamboo species and age, with the pulping conditions at 20% of NaOH, 170ºC pulping temperature, 90 min time to reach pulping temperature and 90 min time at pulping temperature, 1:6 of bamboo to liquor ratio and 0.1% of AQ based on bamboo oven-dried weight. The paper was made according to TAPPI Standard T205 sp-95. The paper mechanical properties for burst index, tear index, tensile index, and folding endurance ranged from 1.32 to 2.36 kPa.m^2/g, 7.48 to 14.9 Nm^2/g, 16.02 to 29.68 Nm/g, and 2 to 28 double folds, respectively, at different bamboo species and age. It was found that *Beting* bamboo has the potential to be a viable raw material for pulp and paper products as it shows the highest mechanical properties compared to *Aur* and *Semantan*.

Keywords: Bamboo age, bamboo species, paper mechanical properties, pulping yield, soda-AQ pulping

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INTRODUCTION

The emergence of the Information and Communications Technology (ICT) era for the past decade has given many benefits to us, so much so our daily activity, whether at home or office, is mostly dependent on the use of the internet. Management and administration in the office have become much faster and more efficient through the internet, while at home, e-commerce or online shopping has become increasingly more comfortable without the need to visit the physical store anymore. These dynamic changes move at a pace we have never imagined possible before. The reduction of huge paperwork and physical documentation in place of emails and the internet could lead to the ideal situation of a paperless society. As much as this is a very encouraging move and drive-by society, the demand for paper has appeared to be steadily going strong regardless of the world's society is going paperless or not. In fact, in 2020, the world consumption of paper and board is expected to reach 426 million metric tonnes. The two world's largest paper and cardboard product users are China and the United States. China consumed nearly 110 million metric tonnes of paper and cardboard in 2018, while the United States consumed 70.6 million metric tonnes (Garside, 2020).

The beginning of paper as a medium for writing took place in 105 A.D. when an old rag and plant tissues were used as paper by T'sai Lun from China, then the art of papermaking slowly traveled to the west (Biermann, 1996; Fatehi et al., 2010). Nowadays, the wood-based pulp has become the main source of papermaking raw material, but the increasing demand for paper-based products has forced researchers to find new alternative raw materials. Furthermore, the development of new technology impacts the pulp and paper industry; it has been proven that new types of paper have been produced, such as nano-paper, groceries package, carbonless paper, and many more. In addition to this, in 2020, the estimated demand for paper would be over 14 million tons (Sharma et al., 2015; Tewari et al., 2009). Thus this would increase the demand for wood as a base material and lead to massive deforestation and replantation that would cause the ecological balance and climatic condition (Rodríguez et al., 2008; Sharma et al., 2015).

Therefore, an alternative to wood is now being sourced, such as non-wood and less expensive raw material (Alagbe et al., 2019). It has been reported that 5-7% of worldwide total pulp and paper production was from non-wood raw material, mostly from straw, bagasse, reeds, bamboo, and others (Polyium et al., 2019). From the paper history, the first paper produced in China was made from non-wood fibers, i.e., cut from bamboo. Egyptians also used non-wood fiber, i.e., papyrus, reeds, and ramie, as a medium for communication and wrapping material for Egyptian mummies. It is interesting to note that the use of trees for papermaking applications, particularly softwood was at a later development as early as the 17th century by the Western in Europe.

Pulp and paper mills in Europe, Japan, and America use trees as their main feedstock for papermaking, whereas countries in the Indian sub-continent, Vietnam, and China rely on non-wood materials such as bamboo, bagasse, cotton ramie, and kenaf for their fiber source. The reason for selecting or using non-wood material is because it is native to those countries and their availability. Besides that, encouraging attribute, the non-wood is a fast-growing plant, requires small land areas, and has a short harvesting period, thus enabling twice or more harvesting exercises in a year which could lead to increased productivity. Bamboo has become one of the promising raw materials for pulp and paper because it has a short mature cycle compared to woody plants. Despite being in the same age group, different species of bamboo have varied mechanical qualities, according to this study.

Bamboo is classified as a grass, with over 70 genera and 1450 species. Bamboo species grow in various climates, from the coldest mountains to the hottest tropical areas (Win et al., 2012). One of Asia's most commonly used non-wood raw materials for the development of paper and paperboard for reasons in terms of fiber length, bamboo can be classified as a long-fibred or semi-long-fibred fibrous material (Li et al., 2012). Despite having chemical characteristics and fiber structures similar to wood, bamboo is a great source of biomass that is undervalued. Bamboo properties have been recorded to vary with species, age, region, and external factors in subtropical countries such as China but the mechanical properties of bamboo vary significantly with a position in a tropical country like Malaysia, but the variations are minor, thus resulting in different processing methods and product quality (Hisham et al., 2006).

This paper reports on the investigation of the mechanical properties of bamboo at different species and ages, which are *Bambusa vulgaris (Aur), Gigantochloa levis (Beting)*, and *Gigantochloa scortechinii (Semantan)* at the age of 1, 3, and 5-year old. The mechanical properties are usually used to measure the strength properties of the paper. There are four basic tests stated by the Technical Association of Pulp and Paper Industry (TAPPI) test method to measure the paper properties, which are tensile strength, bursting strength, tearing resistance, and folding endurance (Caulfield & Gunderson, 1988). Table 1 shows the previous study of fiber morphology of bamboo. The bamboo has a thinner cell wall and thicker lumen diameter; thus, it can produce higher mechanical properties of paper.

Table 1
Fiber morphology of bamboo

Sample	Lumen Diameter (μm)	Cell Wall Thickness (μm)
Aur	6.28	3.16
Beting	8.96	2.71
Semantan	7.22	3.34

Source. Nur Musfirah et al., 2021

MATERIALS AND METHODS

Preparation of the Raw Materials

The three species studied in this project were *Bambusa vulgaris* (*Aur bamboo), Gigantochloa levis (Beting bamboo),* and *Gigantochloa scortechinii (Semantan bamboo)*. The bamboo was harvested 1 foot above the ground and up to 16 feet in height at ages 1, 3, and 5 for all the species, and only one bamboo culm per sample. First, all the samples were collected from Forest Research Institute Malaysia (FRIM) plantation area. After that, the sample was stored in a sample storage room for the next step. Proper storage is important to avoid sample contamination, and the temperature for the storage room was 27°C. Then, the bamboo culms were chipped using a chipper machine before the sample could be turned into a bamboo pulp. Next, the sample must go through the screening process by using a chip classifier to get the uniform size of the bamboo chip. The sample size used was 10-30 mm long and 2-5 mm thick, as stated by Johnsen (2017).

Bamboo Pulping

Pulping's main goal is to isolate the fibers from one another. There are two major pulping processes currently in use: mechanical pulping and chemical pulping (Win et al., 2012). In this study, soda-Anthraquinone (AQ) pulping, which is chemical pulping, was used to digest the bamboo into pulp. 1000 g of bamboo chips based on their oven-dried weight were used for the pulping process, with the moisture content (MC) of 60–73% used for the pulping process and placed into the rotary digester. The pulping parameters used for the pulping were 20% of NaOH, 170ºC pulping temperature, 90 min to reach pulping temperature and 90 min at pulping temperature, 1:6 of bamboo to liquor ratio, and 0.1% of AQ. Only one pulping process was conducted for each species and age, and the pulping condition was chosen based on the previous study made by Nurul Husna et al. (2013). Then the pulp was washed to remove the remaining black liquor from the pulp. For the screening process, only the pulp that can go through the 0.15 mm slot size was used for papermaking as stated in TAPPI standard T 275 sp-9 (Walkinshaw, 2007). The spinner was used to remove the excess water from the screened pulp, and the total pulp yield was calculated, then the pulp was stored inside a cold chiller at the temperature of 6ºC. The pulp yield and total yield was calculated based on Equation 1.

$$\text{Yield} = (A / B) \times 100 \qquad (1)$$

Where Total Yield = Screened Yield + Reject Yield
A: Weight of oven-dry pulp after pulping
B: Weight of oven-dry bamboo chip before pulping

Papermaking and Paper Testing

TAPPI Standard T 205 sp-95 was used to conduct the papermaking process. The moisture content (MC) of the pulp was determined before the papermaking process. First, 24 g of oven-dried weight pulp with the MC of 60–73% was weighed for each batch of paper. Then, 2000 ml of distilled water was added, and the sample was disintegrated inside a disintegrator (AEI Limited, U.K) at 3000 rpm. 1000 ml of pulp stock was used for the freeness measurement. Then the stock was stirred to ensure the proper mixing of the paper stock. For each papermaking sheet, 1000 ml of paper stock was used (TAPPI, 1995). The physical and mechanical properties of paper were tested according to TAPPI standard methods as listed in Table 2, and the size of each paper was 200 cm^2.

Tearing resistance is a measurement of the paper's notch sensitivity. The tearing resistance of paper can be measured in a variety of ways, one of the most useful methods to determine tearing resistance is the Elmendorf method. The method is carried out by creating a crack in the test piece and pulling the paper apart with a perpendicular load to the forehead (Sundblad, 2007). At the onset of the tear, the fracture surface is 90 degrees to the face and nearly 180 degrees at the end. A swinging pendulum completes the ripping, and the energy used during the ripping is recorded The L&W Tearing (No. 5374) (AB Lorentzen & Wettre, Kista, Sweden) was used to measure the tearing resistance. The tearing resistance is expressed in mN and is calculated by dividing the total work by the length of the test piece (Sundblad, 2007). TAPPI T414 om-98 was used to determine the tearing resistance with a paper measurement of 63 mm x 63 mm (TAPPI, 1998).

The bursting test is typically used to evaluate the intensity or durability of paper quickly and easily. The amount of force necessary to burst a paper sample held within annular clamps and subjected to force from one direction is referred to as bursting power. It forces the sample to deform into a roughly semicircular shape before it ruptures and fails. TAPPI T 403 om-97 was used to test the paper sample (TAPPI, 1997).

TAPPI T 511 om-96 was used to evaluate the Fold endurance, and the paper measurement for folding was 15 mm x 159.2 mm (TAPPI, 1996). Fold endurance is a metric that determines how many times a piece of paper can be folded before it fractures when subjected to steady stress (Walkinshaw, 2006). The number of double folds is used to calculate folding strength, while the $\log_{10}$ of the number of double folds is used to calculate folding endurance (Williams & Krasow, 1973). Fiber strength, the fibers' capacity to properly delaminate at the score, and sheet pliability are all factors determining this. In the study made by Seth (1990), folding endurance improves as fiber density rises, thus demonstrating that folding endurance reduces significantly as fiber strength drops. Folding endurance test is the measurement of the ability of paper to maintain its strength after repeated folding under a predetermined load, i.e., normally 800g or 1 kg). The folding test is useful for a paper that has undergone repeated bending, folding, and creasing. Fiber length and fiber bonding give effect to folding test value.

Tensile strength is measured in kN/m and is described as the breaking pressure divided by the strip width, and the tensile index is calculated by dividing the tensile strength by the grammage, and the unit is kNm/kg (Karlsson, 2010). TAPPI T494 om-01 was used to evaluate the Tensile strength, and the paper measurement for tensile strength was 15 mm x 159.2 mm (TAPPI, 2001). The highest tensile force generated in a test specimen before breakage on a tensile test conducted to breakage under regulated conditions is referred to as tensile strength (Muchorski, 2006).

Table 2
TAPPI standard for mechanical paper testing

Mechanical paper testing	TAPPI standards
Tearing index	T414 om-98
Folding endurance	T511 om-96
Tensile index	T494 om-01
Bursting index	T403 om-97

RESULTS AND DISCUSSION

Pulp Yield of Each Species and Age

Pulp yield is the recovery of the fiber after the pulping process. Figure 1 displays a comparison of bamboo pulp yield between ages. The highest pulp yield was *Semantan* (SMT) which is 51.69% at age 1 and the lowest pulp yield was *Beting* (BTG) at age 5 (35.7%). Bamboo SMT age 1 shows results between the range of an unbleached pulp yield for bamboo species *Melocanna baccifera* (50.3-52.3%) recorded by Tripathi et al. 2018, and give higher result than the bamboo species *Bambusa stenostachya* 45.6-48.3%. Nurul Husna et al. (2013) reported that the *Semantan* bamboo at age 3 with a soda-AQ pulping (20% of NaOH, 170ºC pulping temperature) have a pulping yield of 38.70%, which is lower than bamboo at age 1 for *Semantan* (51.7%), *Aur* (41.0%), and *Beting* (43.8). The Runkel ratio for bamboo at age 1 also has lower than 1 for *Semantan* and *Beting* compared to the other age, this shows in a previous study made by Nur Musfirah

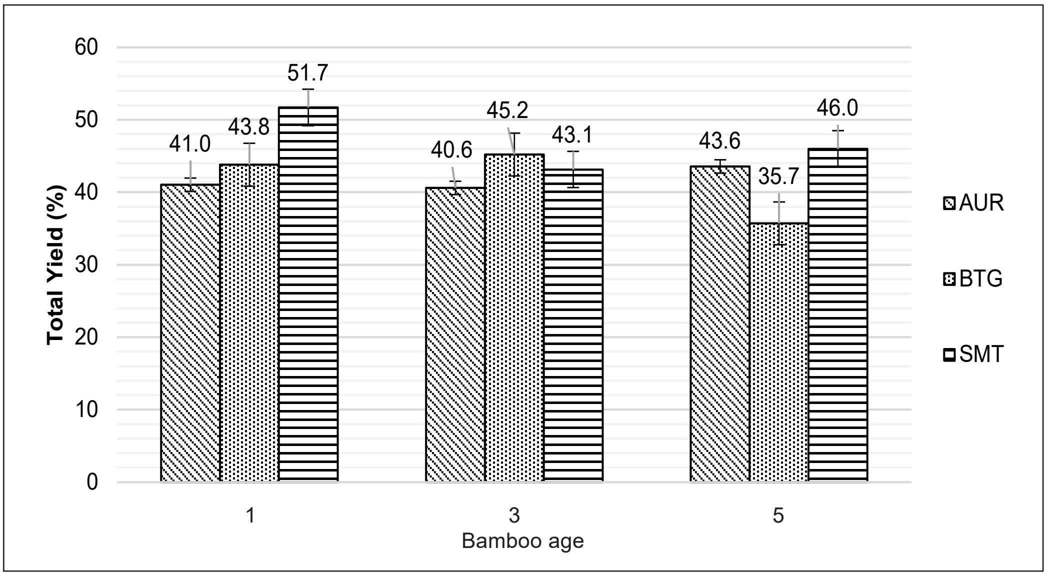

Figure 1. Bamboo pulp total yield for different age
*BTG: *Beting*, SMT: *Semantan*

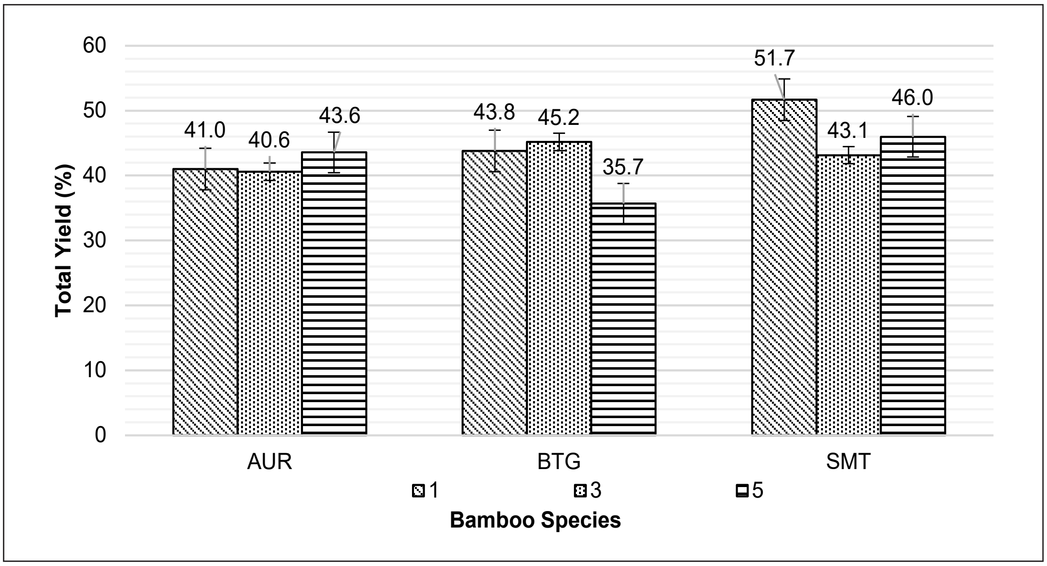

Figure 2. Bamboo pulp total yield for different species
*BTG: *Beting*, SMT: *Semantan*

et al. (2021). Thus this shows that bamboo at age 1 is suitable for papermaking and more economical to use as pulp and paper raw material. Therefore, the bamboo at age 1 was used to study the mechanical properties of unbeaten bamboo paper. Figure 2 shows the comparison of pulp yield between the species; *Semantan* gives the highest pulp yield compared to *Aur* and *Beting*.

Paper Mechanical Properties

Mechanical properties of paper are important to distinguish whether the material is suitable for pulp and paper, along with the durability for the material to withstand any wear, pressure, or damage. The durability of papers with randomly distributed fibers is based on the individual fiber strength as well as the strength and number of links between them (Kallmes and Perez, 1966; Page 1969; Van den Akker et al., 1958).

In an attempt to avoid bias to the paper strength, the grammage will be divided with the burst, tearing, and tensile strength to get the burst, tearing, and tensile index. As a result, the dry solids content of the paper web increases from about 20% to 40% during pressing in the press section of the paper machine. In addition, surface friction in the liquid meniscus created at the contact intersection of two fibers causes capillary forces to pull the fibers together. The increasing capillary forces are also due to the mechanical entanglement of fibrils that pull fibers and fines closer together, leading to a stronger network (Sundblad, 2007). Table 3 exhibits the mechanical properties of bamboo and other non-wood paper.

Beting paper gives the highest result for burst index (2.4 kPa.m^2/g), tear index (14.9 Nm^2/g), tensile index (29.7 Nm/g), and fold endurance (28 double folds), followed by *Aur* paper. The lowest mechanical paper properties were the *Semantan* pulp which are 1.3 kPa.m^2/g (burst index), 7.48 mN.m^2/g (tear index), 16.02 Nm/g (tensile index), and 2 double folds (fold endurance). *Beting* shows significant differences for burst index, tear index, tensile index, and folding endurance. Meanwhile, there are no significant differences between *Aur* and *Semantan*. Generally, tensile and bursting strengths of papers made from hardwoods respond to the same fiber morphological effects as do softwoods. Fiber length and cell wall thickness significantly impact bursting and tensile strengths, which seem to be reliant on the development of fiber-to-fiber linkage (Horn, 1978). Besides bamboo, Table 3 also displays some examples of treated non-wood paper mechanical properties. The data showed that corn sheath has a higher burst index (2.9 kPa.m^2/g) than *Beting* (2.4 kPa.m^2/g) but is lower in tear index and tensile index compared to *Beting*. All bamboo samples also give a higher burst index and tensile index compared to kenaf bast and date palm.

The flexibility and collapsibility of the fiber have a positive impact on the mechanical properties of bamboo paper. The ability of the fibers to bind around other fibers is affected by flexibility, which affects the number of fiber-to-fiber interactions, the number of bonds, and the bonded region in the layer (Sundblad, 2007). In addition, fiber flexibility influences the number of bonds, representing the number of bonding areas. Bonding will be easier with a flexible fiber because it has more surface area. Paper tensile and bursting strengths are two qualities that are heavily reliant on interfiber bonding. Table 1 shows the previous study of the fiber morphology of bamboo (Nur Musfirah et al., 2021). The data showed

Table 3
Mechanical properties of bamboo and other non-wood paper

Specific properties	unit	Paper sample					
		Aur	*Beting*	*Semantan*	Kenaf bast^X	Date palm leaves^X	Corn sheath^Y
Grammage	g/m^2	61.98	61.55	62.81	n.a	n.a	n.a
Thickness	mm	0.70	0.56	0.69	n.a	n.a	n.a
Burst index	kPa.m^2/g	1.44^a (0.1)	2.36^b (0.2)	1.32^a (0.1)	n.a	1.4	2.9
Tear index	mN.m^2/g	9.02^b (0.6)	14.9^b (0.5)	7.48^b (1.13)	11.84	8.4	2.21
Tensile index	Nm/g	18.8^a (1.2)	29.68^b (0.4)	16.02^a (0.5)	2.09	13.8	3.9
Fold endurance	double folds	3^a (0.4)	28^b (1.1)	2^a (0.0)	n.a	n.a	n.a

Mean with the same letters are not significantly different ($p \leq 0.05$)
n.a: not available, X: (*Ashuvila, 2014*), Y: (*Alagbe et al., 2019*)
Number in the bracket indicates the standard deviation (SD) within the samples

that the *Beting* bamboo fiber has the lowest cell wall thickness (2.71 µm) and higher lumen diameter (8.96 µm), thus giving more flexibility and collapsibility for the fiber to fiber bonding.

The more fibers that can collapse and entangle, the more bonding surface is available for other fibers to bind. It is thought to be one of the most important factors in tensile strength. Individual fiber strength can be considered a factor, but if the bonding between the fibers is weak, the fibers will be pulled out (Sundblad, 2015). Therefore, bonding produces higher mechanical properties for the *Beting* bamboo paper. Fiber length and fiber coarseness significantly affect the tearing and tensile strengths of the paper. Fiber length has a greater effect on the tearing property in a poor interfiber bonded paper, and the effect becomes less significant with an increase in the fiber-bonding strength. As the fibers coarser, tearing strength increases and tensile strength decreases (Liu et al., 2006; Seth, 1995).

CONCLUSION

Bamboo could be a promising alternative raw material for pulp and paper products. The mechanical properties of bamboo showed that it has the potential to be used for papermaking. *Beting* unbeaten paper showed the highest in burst index (2.4 kPa.m^2/g), tear index (14.9 mN.m^2/g), and tensile index (29.684 Nm/g) compared to *Aur* and *Semantan* pulp. Compared with other non-wood pulp such as corn sheath, the *Beting* unbeaten pulp shows a slightly lower burst index. Thus mechanical treatment such as beating is needed to improve the strength of bamboo pulp. Beating will create internal and external fibrillation on the fiber; hence it will create more bonded area and improve the mechanical properties of the paper.

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