
Alkaline Sulfite Anthraquinone and Methanol (ASAM) Pulping Process of Tropical Bamboo (*Gigantochloa scortechinii*)

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Abstract

This chapter explores the characteristic potentials of alkaline sulfite anthraquinone and methanol (ASAM) pulping of bamboo culms (*Gigantochloa scortechinii*) in the industrial production of pulp and paper for packaging. The biometric characterization results of the bamboo culms show that bamboo has fiber length of 1980–4000 μm , Runkel ratio of 0.86, and flexibility ratio of 50.19, while the chemical compositions of the bamboo contain 47.67% cellulose, 68.33% holocellulose, 26% lignin, and 3.69% solvent extractive, which give good paper quality fiber and also falls within the range of wood from softwoods species. The study revealed that the optimum ASAM pulping parameters was at 16% NaOH and 90 min cooking time, resulting in Kappa number of 14.17 and pulp yield of 49.06%, while the paper tensile index of 20.86 Nm/g, tear index of 22.64 mN.m²/g, and brightness of 39.32% were obtained. The biometric and chemical characterizations of the ASAM pulped bamboo have shown that ASAM pulped bamboo produces high-quality pulp and paper suitable for packaging and printing paper. Hence, the use of bamboo materials can reduce the burden on the forest, due to the increasing demand for paper and paper products, while supporting the natural biodiversity.

Keywords: alkaline sulfite anthraquinone and methanol, ASAM, pulping, bamboo, pulp and paper

1. Introduction

Despite the global digital revolution and consequence to the variation in the global regional market shares with respect to the production capacity and consumption pattern, the pulp and paper industry has experienced dramatic growth in the recent years. The recent trend of packaging that is gaining consumer's attraction is the emergence of paper and paperboard packaging due to its effective solutions in food and beverages, healthcare, manufacturing, personal care and other industries [1]. The demand of innovative and convenient packaging features is synonymous to the changing lifestyle of people. Conversely, the growth of the pulp and paper industries has been hindered since the major raw material for pulp and paper manufacturing is wood, which is drastically depleting. The industries are saddled with various challenges from ecological protocols, energy consumption and economic survival; therefore, modified technologies that are environmentally benign and economically viable are being sought to enhance the survival of the industries through the twenty-first century and beyond. Various researchers have reported the replacement of wood with non-wood as the immediate panacea to the challenges in the pulp and paper industries. In the array of these non-woods is bamboo, which is a fast-growing monocotyledon plant found in temperate, subtropical and tropical areas with diverse groups of plant in the grass family with 75 genera and 1250 species of bamboo worldwide [2]. Conventionally, bamboo has gained commercial usage in the field of construction (poultry cages, shade blinds,, furniture and handicrafts (vegetable baskets, incense sticks, tooth picks, chopsticks, skewers, barbeque sticks and joss paper) [3].

1.1. Socio-economic benefits of bamboo

Traditionally, being one of the oldest materials used worldwide with wide applicability, bamboo industry is a flourishing business especially at the small-scale level. Since the engine that drives the growth of any economy is the small-scale industries, bamboo business plays a very significant role in the overall growth of an economy. Statistics revealed that of all forests in the world, bamboos occupy approximately 36 million hectares at the rate of present expansion of 3.2% of total forest area [4]. Bamboo can be divided into four regions based on supply chain in various continents of the world and this include Asia-Pacific bamboo region (India, China, Indonesia, Myanmar and Malaysia) [5, 6], which contributes about 65% global supply of bamboo. This is closely followed by American bamboo region (North American and Latin American countries) which contributes about 28% and African bamboo region which contributes about 7% supply. Asia-Pacific bamboo region is expected to continue to dominate the global bamboo market both in terms of value and volume by 2027. Consequently, the cumulative average growth rate (CAGR) of bamboo is projected at 11.8% CAGR. Hence by the end of 2027, nearly three-fourth of global bamboo revenue will be accounted by the region [7]. This projection is based on the versatility of bamboo entrepreneurship, which ramifies wood and furniture (timber substitute, plywood, mat boards, flooring, furniture, outdoor decking), construction (scaffolding, housing, roads), food (bamboo shoots), pulp and paper, textile, agriculture, charcoal and handicrafts, regarded as being one of the key instruments in uplifting the

socio-economic status of the poor and underprivileged people in a community. Being the largest consumer of lignocellulose biomass, pulp, paper and paper packaging industries are expected to benefit from this wide availability of bamboo.

2. Suitability of bamboo for pulp and paper

Amid the collection of non-wood natural fibers, bamboo has gained wide applicability in pulp and paper industry. Several reports on the potential of bamboo revealed its potential as a better raw material for pulp and paper packaging because of its long fiber, since the fiber length is an important factor in paper making. The fiber length is similar with what is obtained in softwood fiber properties, hence making bamboo as an ideal replacement in pulp and paper manufacture. For instance, the fiber length has impacts on the physical and mechanical properties of paper such as tear strength and folding endurance. These spectra of properties make bamboo very economical in terms of management and can easily be transported to the pulp and paper mills [8].

The large lumen width and fiber diameter characteristic of bamboo contribute positively to the effective beating process [9]. Like other wood species bamboo fibers have many similar benefits than wood such as: (1) bamboo can be chipped in a similar manner to wood, (2) bamboo is a low-cost crop due to low maintenance, (3) bamboo chips can be blended with wood chips and (4) bamboo is a fast-growing fiber source. Almost all studies suggested that papers made from bamboo are relatively stronger than those made from softwood. Successful development of bamboo pulping requires a technology which is able to exploit the full potential of this raw material. Specifically, this means that selectivity in pulping and bleaching has to be on a high level resulting in pulps with high yield and good strength properties.

2.1. Biometric characteristics of *G. scortechinii*

Table 1 shows the biometric characterization of the studied bamboo (*G. scortechinii*) species compared with some other natural fibers for pulp and paper making. From the table, it means that the bamboo species under study possesses relatively long fibers, 1980 μm , compared to Eucalyptus (840 μm), *B. tulda* (1890 μm) and cotton stalks (810 μm).

Many studies have reported that the fiber length of bamboo is generally greater than hardwood and is similar to softwood [14]. Fiber length may actually be a detriment to good strength properties, as in the case of certain non-wood fibers, such as bamboo, bagasse and cotton. In such a case, fibers are longer than 2 μm [15]. The long fibers are covered with fibrils, fines, and the large fibrils effectively serve to bridge the gaps between the naturally rough surfaces of adjacent fibers. In this way, long fibers have an effect on the strength of a bond and especially its toughness, which is characteristic of the bonds between natural paper making fibers and which is completely lacking with bonds between smooth viscose fibers. On the other hand, water drains from long fiber pulps more rapidly, and this is a point in their favor. Therefore, for pulp and paper production, species with higher fiber lengths are preferred since a better fiber net can be achieved, resulting in a paper with high resistance. The biometric characteristic of *G. scortechinii* shows favorable properties as a fiber raw material for pulp and paper.

Biometric parameters	Type of fibers				
	<i>G. scortechinii</i>	<i>Bambusa tulda</i>	<i>Eucalyptus grandis</i>	Cotton stalk	Spruce
FL (μm)	1980 ± 3.3	1890	840	810	19
FD (μm)	17.27 ± 3.7	3.45	10.1	16.75	10
LD (μm)	8.66 ± 2.3	6.78	4.4	4.12	4.5
CWT (μm)	0.86 ± 0.20	3.93	0.87	0.49	0.9
Runkel ratio	50.14 ± 3.6	20.29	53.15	67.05	52.63
Flexibility ratio	114.64 ± 3.6	111.2	44.21	32.42	152.63
Slenderness ratio	This study	[10]	[11]	[12]	[13]

FL = fiber length, FD = fiber diameter, LD = lumen diameter, CWT = cell wall thickness, Runkel ratio = $(2 \times \text{CWT})/\text{LD}$, Flexibility ratio = $(\text{LD}/\text{FD}) \times 100$, Slenderness ratio = (FL/FD) .

Table 1. Biometric characteristics of bamboo and other natural fibers.

The average fiber diameter of *G. scortechinii* is $17.27 \mu\text{m}$ which is in the range of other species of *Bambusa* genera. The lumen diameter and cell wall thickness of bamboo was $8.66 \mu\text{m}$ and $3.74 \mu\text{m}$, respectively. The lumen diameter and cell wall thickness influence the beatability of fibers. Fibers with large lumen diameter and thin walls such as in bamboo have higher bonding abilities due to the better penetration by water into the cell wall and into the lumen causing the cells to swell. The combined effects of the beating action and swelling cause the bonds between the structures of lamellas to loosen and easily separate [16].

2.2. Chemical compositions

The chemical compositions of *G. scortechinii* are shown in **Table 2**. The results showed that the *G. scortechinii* had high contents of ash and silica (1.98 and 1.56%, respectively), but the results were within the range of tropical hardwood, which is 1–3% [20].

The mechanical properties of final paper are related to the amount of hemicellulose and cellulose contents of raw materials. In addition, polysaccharides such as cellulose and hemicellulose have a positive effect on pulp yield of alkaline pulping process [21]. Raw material with more than 34% of cellulose content can be used for pulp and paper production [22]. The cellulose content of *G. scortechinii* is in the range of both soft and hardwood, 40–52% and 38–56%, respectively [23]. The cellulose molecule has numerous hydroxyl groups, which have a strong tendency toward hydrogen bonding with hydroxyl of adjacent molecules [24]. This tendency in connection with the molecular structure is responsible for increasing fiber-to-fiber bonding in final paper [25, 26]. The free hydroxyl groups of cellulose have a strong affinity for polar solvents and solutes that can reach them. An example of this type of interaction is the swelling of cellulose with water. During swelling, the hydrogen bonds between cellulose molecules are broken and replaced by hydrogen bonds between the cellulose molecular and water. Therefore, the cellulose content in the surface of fibers formed with water was a true chemical hydrate and, being glue-like, caused the strength of the resulting paper to increase as well [27].

Composition %	Natural fibers			
	<i>G. scortechinii</i>	<i>P. bambusoides</i>	Rice straw	<i>P. orientalis</i>
Holocellulose	68.33 ± 3.7	70.50	70.90	74.46
Cellulose	47. 67 ± 3.4	43.30	48.20	44.31
Lignin	26. 00 ± 2.3	24. 50	17.20	25.20
Solvent extraction	3.64 ± 3.2	3.90	3.50	3.40
1% NaOH	19.82 ± 3.5	25.10	49.20	10.26
HWS	5.53 ± 1.2	6.50	16. 20	2. 81
CWS	4. 61 ± 1.4	—	10.70	1.47
Ash	1.98 ± 0.33	1.40	16.60	0.32
Silica	1.56 ± 0.25	—	14.90	—
Reference	Present study	[17]	[18]	[19]

SE = solvent extractives (ethanol-benzene), HWS = hot water solubility, CWS = cold water solubility, and 1% NaOH = 1% sodium hydroxide solubility.

Table 2. Comparison of the chemical compositions of bamboo with other natural fibers.

The lignin content of *G. scortechinii* is 26%, which is less than the tropical hardwood. Also, *G. scortechinii* contains about 3.68% solvent extractive which is quite similar to softwood (3%) but is less than solvent extractive reported for hardwood. *G. scortechinii* has high 1% NaOH solubility (19.82%). 1% NaOH solubility of *G. scortechinii* shows that more low molecular weight components such as hemicellulose could be solved during the alkaline degradation. As a result, the pulp yield of alkaline pulping of bamboo could be decreased and consumption of alkali charge could be increased due to this property [28, 29]. The hot and cold water solubility of bamboo culms were 5.53 and 4.61%, respectively. Extraction with hot water removes carbohydrate materials such as starches. Extraction with cold water removes sugars, gums, tannins, and inorganic compounds [30]. As it is shown in **Table 2** the ash content of *G. scortechinii* was 1.98%. The ash content of bamboo culms was higher than the aspen and white oak with values of 0.43 and 0.87%, respectively [31]. The silica content of *G. scortechinii* was 1.56%, which is low compared with non-wood species such as rice (14.9%) and wheat straw (4.35%). Silica results in many problems such as blunting of saw tooth, scaling during chemical recovery of black liquor and covering the outer surface of fiber during cooking. On the other hand, the silica is dissolved in alkali solutions; therefore, the consumption of alkali charge in cooking liquor is increased [32].

3. Pulping of bamboo (*G. scortechinii*)

Traditionally, kraft pulping has been the most commonly reported pulping milieu for bamboo species [33]. This is due to its strong bundle sheathes, impenetrable epidermis, a complete absence of ray cells and limited area of conducting tissues. As good as this pulping technique

is, it is saddled with a lot of environmental legislative issues. The present paradigm shift in the pulp and paper making toward environmental benign pulping has informed the search for better pulping method for bamboo species.

3.1. Drawbacks of the conventional commercial pulping technique

The conventional commercial pulping procedures of annual plants include both kraft and soda pulping. The major drawback of these pulping protocols is that in the case of alkaline cooking liquors, apart from the delignification process, significant decomposition of carbohydrates portion of the lignocellulose biomass is observed by peeling-off reactions and alkaline hydrolysis. Optimum alkaline cooking condition is pertinent as excess alkaline loading could result in lowering of the ISO brightness due to the concept of alkaline darkening. Furthermore, sodium hydroxide easily dissolves phenolic lignin structures; besides, lignin undergoes condensation reactions under strong alkaline conditions which reduce the reactivity of residual lignin. In the like manner, strong alkaline cooking liquors dissolve high silica content of annual plants and precipitates evaporation problems in soda recovery boilers and in the causticizing plant [34].

In contrast, conventional kraft pulping has been used commercially for paper packaging from annual plants such as wood and some bamboo species, due to good paper properties. Kraft pulping has been found suitable for all ranges of fiber sources. It gives paper of high tensile strength and also high efficiency of the recovery of cooking chemicals [35]. In non-phenolic lignin moieties only β -ethers are cleaved. This has also an impact on bleaching. Among the disadvantages of kraft pulping process, low yield pulp, high consumption of bleaching chemicals, emission of obnoxious odor from the pulping process and large mill size require a tremendous capital investment.

Compared to soda pulps, soda/anthraquinone (soda/AQ) pulps have slightly better bleaching ability, higher yield and sometimes better strength. Similarly, alkali sulfite pulping had been known to give good strength properties and significantly higher yields than kraft process [36]. The addition of anthraquinone helped to reduce Kappa number from the unbleached pulp.

In order to overcome the abovementioned challenges, Patt and Kordsachia [37] discovered that the addition of methanol or ethanol extended delignification to levels below kraft or sulfite pulps. They named their process as alkali-sulfite-anthraquinone methanol (ASAM). Unlike the conventional pulping protocols, ASAM pulping process has dual advantages of paper properties and higher pulp brightness. In addition, ASAM pulping results in pulp with high pulp yield, low Kappa number and high paper strength. Furthermore, the obnoxious odor from methyl mercaptan that is generated during kraft pulping is completely absent in ASAM pulping.

3.2. Mechanism of alkaline sulfite anthraquinone and methanol (ASAM)

Alkaline sulfite anthraquinone with methanol pulping known as the ASAM process was developed by Patt and Kordsachia in 1986 as an alternative cooking process option for soda

and kraft pulping processes. According to the authors, the chemical materials that make up the ASAM process are sodium sulfite (Na_2SO_3), sodium hydroxide (NaOH), anthraquinone (AQ) and methanol (CH_3OH). These materials play a unique role in the pulping milieu because, sodium sulfite and sodium hydroxide are the major ingredients of the alkaline sulfite process while the anthraquinone and methanol act as catalysts to enhance the chemical penetration delignification of the lignocellulose biomass. **Table 3** shows the characteristics of cooking parameters in the ASAM pulping process, while **Table 4** gives a summary of the key role of each chemical constituent in ASAM blend.

The mechanism of ASAM pulping process can be viewed with respect to the cooking parameters.

3.2.1. Effect of sodium hydroxide addition in ASAM pulping

Sodium sulfite and sodium hydroxide are two major active constituents in ASAM pulping process playing the dual role of delignification and increasing pulp brightness. Several research trials toward the effect of replacement of sodium hydroxide with sodium carbonate

Cooking parameters	Value
Total alkali (NaOH)	20–25 o.d
Alkali ratio ($\text{Na}_2\text{SO}_3/\text{NaOH}$) or ($\text{Na}_2\text{CO}_3/\text{NaOH}$)	80/20–70/30
Anthraquinone (AQ)	0.075–0.1%
Methanol	10–15 by vol
Temperature	175–180°C
Cooking time at maximum temperature	120–180 min

o.d = oven dry.

Table 3. Characteristic cooking parameters of ASAM pulping process. Source [38].

Cooking parameters	Significance
Total alkali (NaOH)	Accelerant delignification Increases the cooking PH
Alkali ratio ($\text{Na}_2\text{SO}_3/\text{NaOH}$) or ($\text{Na}_2\text{CO}_3/\text{NaOH}$)	Sodium hydroxide accelerant delignification in comparison with sodium carbonate Sodium sulfite changed lignin to solvable material Sodium carbonate generates pulp with the strongest tensile index, highest pulp yield, and highest brightness than sodium hydroxide
Anthraquinone (AQ)	Enhances the delignification rate Act as effective stabilizer in both wood and non-wood polysaccharides
Methanol	Enhances chemical penetration into the woody chips Methanol improves the solubility of the AQ

Table 4. ASAM cooking parameters and their role.

or sodium peroxide in the ASAM pulping process have been reported. The advantage of sodium hydroxide in ASAM pulping is that NaOH tends to accelerate delignification than sodium carbonate; furthermore, by applying NaOH as a source of alkali charge, the initial pH of the white cooking liquor enhances leading to the dissolution of more lignin and carbohydrates (hemicellulose) [38].

Apart from the substitution of sodium hydroxide with sodium carbonate in ASAM pulping, attempt has been made with the use of sodium peroxide. It was reported that sodium carbonate substitution gave better pulp products due to the fact that the sodium carbonate-substituted ASAM mixture gave pulp with the stronger tensile index, higher pulp yield and higher brightness [39] due to greater delignification process. This results from the fact that solution of acid soluble lignin contributed to lignin dissolution. The relatively low pH of spent liquor at high temperature results in the partial cleavage of α -ether bonds in lignin [40, 41]. On the other hand, the use of alkaline sodium sulfite as an additive in the ASAM process produces a low Kappa number, high pulp yield and high brightness. In addition, the production cost is also significantly reduced and the total alkalinity consumption becomes less [38].

3.2.2. *Effect of anthraquinone (AQ) addition*

The addition of anthraquinone (AQ) in white cooking liquor increases the delignification rate due to the rate of decrease in the lignin content of wood or non-wood as the alkali consumption during the alkaline pulping process progresses. This can be divided into three phases: (1) initial reaction, (2) bulk delignification and (3) residual delignification.

In the initial reaction phase, alkali is consumed in deacetylation reaction, in neutralization of wood or non-wood acids and in dissolution of readily soluble wood or non-wood carbohydrate components (hemicellulose, tannins, etc.); hence, very little actual delignification occurs. More lignin is eliminated in the period of bulk delignification phase. This elimination occurs much more quickly than the third stage (residual delignification) [41, 42]. As a result, the proportion of lignin removal in polysaccharides happens slowly. Thus, this is only true when a sufficient amount of alkali charge is available. Thereupon, by adding AQ to the cooking liquid, more alkalinity can be stored for the bulk delignification volume and more lignin can be removed [38, 42]. On the other hand, AQ has the role of an effective stabilizer in both wood and non-wood polysaccharides. AQ is effective at extremely lower dosage levels of 0.05–0.1% on oven-dry wood, giving good results in most cases [43].

3.2.3. *Effect of methanol addition*

The addition of methanol at the initial pulping stage enhances chemical penetration into the woody chips by increasing the solubility of lignin, subsequently, producing a uniform (homogeneous) chemical performance in the cooking time and also suppresses the dissociation of the inorganic pulping chemicals. The trapped air from the woody cells could be removed by raising the pressure of the digester, thus accelerating the penetration of chemicals into the wood cells [44, 45].

In ASAM pulping, it is important to ensure that alkali has penetrated into the center of the chip prior to rising the temperature above 140°C, since undesirable lignin condensation reactions can occur at high temperatures in the absence of alkali [46, 47]. The use of methanol is preferred over ethanol in ASAM pulping protocol because of the lower boiling point that results in lower energy consumption for recovery. In addition, compared to ethanol, methanol has less viscosity, polarity and surface tension. The low surface tension and increased pressure, together with the ability of methanol to dissolve resins, have a positive impact on the penetration of chemicals into the chips [48, 49].

Apart from enhancing chemical penetration during pulping, Sridach [50] discovered that methanol also improves the cellulose stability in the ASAM pulping, hence producing pulp with higher viscosity. This was achieved by suppressing, stopping the reaction or slowing down the transformation of the cellulose aldehydic functional groups into keto groups that initiate the peeling reaction. Due to the use of methanol in the cooking liquor, more penetration of chemicals into the chips occurs. Raising pressure of the digester and more air removal of chips are the two main ways of improving the penetration of chemical materials into wood or non-wood chips. Therefore, adding methanol while an ASAM cooking liquor is in the process of penetrating the chips leads to a higher pressure of the digester. As a result, the entrapped air of the chips is displaced, and chemical materials can penetrate into both wood and non-wood chips. Consequently, more delignification happens and fibers can be easily separated [51].

3.2.4. Advantages of ASAM pulping

In comparison with kraft pulping process, the ASAM pulping process has a higher digester pressure of 1.3–1.4 MPa and the cooking temperature of 5–10° [42]. Several studies have considered the application of ASAM in the cooking process of both hard and soft wood. Moradbak et al. [42] reported that *Eucalyptus globulus* had been cooked by ASAM pulping process, which results in 56.9 and 53.6% pulp yield and 14 and 10 Kappa number, respectively. Pulp yield and Kappa number of *Pinus sylvestris* were found to be from 52.9 to 52.5% and from 31 to 27, respectively [52].

Several reports have shown some of the unique advantages of ASAM pulping process. These include (i) prevention of air pollution, (ii) high delignification rate, (iii) high brightness of pulp, (iv) high pulp yield and (v) ease of pulp bleaching [53].

3.2.5. Reactivity of ASAM pulping

A review of the reactivity of alkaline sulfite anthraquinone and methanol (ASAM) pulping process shows that the information available is relatively scarce, fragmented and yet to gain adequate commercial applications. Previous studies have focused on either sodium-anthraquinone (Soda/AQ) pulping or alkaline sulfite-anthraquinone (AS/AQ) pulping. In pulping process, the parameters that are of most significance with respect to delignification and polysaccharide removal are alkali charge and cooking time [42, 47]. In addition, ASAM pulping process has better selectivity in comparison to kraft or soda pulping processes in terms of delignification, which leads to low Kappa number and high viscosity. Few studies have

Raw material	Pulping parameters	Total yield	Kappa no.	Tensile index (Nm/g)	Burst index (kPa.m ² /g)	Tear index (mN.m ² /g)	Brightness (%)	Reference
Bamboo (<i>G. scortechinii</i>)	NaOH: 16%; AQ: 0.1% Methanol: 15% Na ₂ SO ₃ /NaOH: 80/20 T: 90 min; Temp: 170°C	49.06	14.17	20.86	10.83–9.27	20.86	39.32	Present Study
<i>Hibiscus cannabinus</i>	NaOH: 17%; AQ: 0.1% Na ₂ SO ₃ /NaOH: 70/30 T: 120 min; Temp: 175°C	52.6	15.5	101.9	7.4	9.4	41.9	[54]
Whole jute plant	NaOH: 22%; AQ: 0.1% Na ₂ SO ₃ /NaOH: 80/20 Methanol: 25% T: 60 min; Temp: 170°C	56.6	39.2	—	3.2	11.2	45	[55]
<i>Eucalyptus globulus</i>	NaOH: 22.5%; AQ: 0.1% Methanol: 25% Na ₂ SO ₃ /NaOH: 80/20 T: 135 min; Temp: 180°C	56.7	16.6	53.8	—	4.2	56.6	[56]
<i>Populus deltoids clone</i>	0.1%; Methanol: 10% Na ₂ SO ₃ /NaOH: 80/20 T: 120 min; Temp: 170°C	51	—	59.4	4.8	3.8	45.9	[57]
<i>Eucalyptus globulus labill</i>	NaOH: 25%; AQ: 0.1% Methanol: 30% Na ₂ SO ₃ /NaOH: 70/30 T: 90 min; Temp: 170°C	53.4	17	—	—	—	36	[58]
<i>Trema orientalis</i>	NaOH: 17%; AQ: 0.1% Methanol: 20% Na ₂ SO ₃ /NaOH: 80/20 T: 120 min; Temp: 180°C	52.8	13.4	47.4	4.8	10.7	—	[59]

AQ = anthraquinone, T = time, Temp = temperature.

Table 5. Effects of ASAM pulping parameters on pulp and paper properties of various types of lignocellulosic materials.

considered the application of ASAM in the cooking process of both hard and soft wood. **Table 5** gives the summary of the reported pulping of lignocellulose biomass using ASAM pulping process on different lignocellulose biomass compared with the ASAM pulped bamboo (*G. scortechinii*) species. At a constant ASAM pulping process at 170° and alkali ratio (Na₂SO₃/NaOH; anthraquinone: methanol) of (80/20, 0.1%: 15%), it was found that ASAM pulped bamboo gave a characteristic high yield of 52.36%. Like the other ASAM pulped biomass (**Table 5**) this is quite higher than what is obtainable in kraft pulping. The highest yield was achieved by applying 14% sodium hydroxide and 90 min cooking time while the lowest Kappa number (10.38) was observed using 18% and 120 min. Further increase of both alkali and cooking time resulted in marked decrease in both Kappa number and pulp yield. From the result, ASAM pulping of bamboo (*G. scortechinii*) revealed a low Kappa number compared with what was obtained from *Hibiscus cannabinus*, whole jute plant, *Eucalyptus globulus* and *Eucalyptus globulus labill* as reported by Khristova et al. [54]; Jahan et al. [55]; Kordsachia et al. [56]; and Gominho et al. [58], respectively, despite the high ASAM pulping parameters used.

The tear, tensile and burst indices of unbleached bamboo ASAM paper were within the range of 26.33–18.64 mN.m²/g, 24.8–17.87 Nm/g and 10.83–9.27 kPa.m²/g, respectively, which is suitable for packaging paper. The study revealed that the optimum ASAM pulping parameters were at 16% NaOH and 90 min cooking time, resulting in paper having tensile index of 20.86 Nm/g, tear index of 22.64 mN.m²/g and brightness of 39.32%. Another advantage of this pulping process is to produce pulp with a low proportion of rejected material. Aldonic acid, which is present as a result of isolation from pulp hydrolyzates, indicates that stabilization takes place through conversion of the end group to the acid out of an oxidation reaction [42, 60]. Therefore, according to role of AQ and methanol in ASAM pulping process, one can expect high yields of ASAM bamboo unbleached pulp.

4. Conclusion

The study determined the technical feasibility of bamboo culms (*G. scortechinii*) as a non-wood fiber for pulp and paper industry. For this purpose, the biometric characteristics and chemical compositions, pulping characteristics, paper properties, projects ASAM pulped of *G. scortechinii* as good material for pulp and paper packaging material. The results show that the fiber length of *G. scortechinii* is similar to softwood and had significant effects on the properties of bamboo paper. The Runkel and flexibility ratios of *G. scortechinii* were in the range of spruce (softwood) with 0.86 and 50.14, respectively. Meanwhile, the chemical composition analysis of *G. scortechinii* presented that bamboo have a high amount of cellulose content and lowest solvent extractive content in comparison with other non-wood species. Therefore, the result showed that *G. scortechinii* can produce pulp and paper, which is almost comparable to other sources. It was also found that the pulp properties of bamboo often being subjected to ASAM pulping process were significantly affected (at $p \leq 0.05$) by the cooking conditions. The pulp at 18% NaOH and 90 min cooking time gave low pulp yield and the tear index with values of 41.24% and 18.64 mN.m²/g, respectively. The pulp made at 16% NaOH and 90 min cooking time presented the best properties, pulp yield, Kappa number, tensile, tear and burst indices with values of 49.06%, 14.2, 20.86 Nm/g, 22 mN.m²/g and 10.05 kPa.m²/g, respectively.

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References

- [1] Bras J, Saini S. Nanocellulose in functional packaging. In: Cellulose-Reinforced Nanofibre Composites. Woodhead Publishing Series in Composites Science and Engineering; 2017. pp. 175-213
- [2] Chen J, Yuan Z, Zanuso E, Trajano HL. Response of biomass species to hydrothermal pretreatment. In: Hydrothermal Processing in Biorefineries. Cham: Springer; 2017. pp. 95-140
- [3] Chakraborty S, Chaudhuri PS. Earthworm communities in the bamboo plantations of West Tripura (India). Proceedings of the Zoological Society. Springer India. 2017;**70**(2):105-118
- [4] Wang Y, Bai S, Binkley D, Zhou G, Fang F. The independence of clonal shoot's growth from light availability supports moso bamboo invasion of closed-canopy forest. Forest Ecology and Management. 2016;**368**:105-110
- [5] Banik RL. Bamboo silviculture. In: Bamboo. Springer International Publishing; 2015. pp. 113-174
- [6] Ling M, Christensen M, Donnison A, Belmonte KD, Brown C. Scoping Study to Inform the Global Assessment of Bamboo and Rattan (GABAR). Cambridge, UK: UN Environment World Conservation Monitoring Centre. 2016
- [7] Catacutan DC, van Noordwijk M, Nguyen TH, Öborn I, Mercado AR. Agroforestry: Contribution to Food Security and Climate-Change Adaptation and Mitigation in South-east Asia. White Paper. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program; Jakarta, Indonesia: ASEAN-Swiss Partnership on Social Forestry and Climate Change. 2017
- [8] Dai L, Long Z, Chen J, An X, Cheng D, Khan A, Ni Y. Robust guar gum/cellulose nanofibrils multilayer films with good barrier properties. ACS Applied Materials & Interfaces. 2017;**9**(6):5477-5485

- [9] Akeem Azeez M, Andrew JE, Sithole BB. A preliminary investigation of nigerian *Gmelina arborea* and *Bambusa vulgaris* for pulp and paper production. *Maderas. Ciencia y Tecnología*. 2016;**18**(1):65-78
- [10] Sharma AK, Dutt D, Upadhyaya JS, Roy TK. Anatomical, morphological, and chemical characterization of *Bambusa tulda*, *Dendrocalamus hamiltonii*, *Bambusa balcooa*, *Malocana baccifera*, *Bambusa arundinacea* and *Eucalyptus tereticornis*. *BioResources*. 2011;**6**(4):5062-5073
- [11] Malik RS, Dutt D, Tyagi CH, Jindal AK, Lakharia LK. Morphological, anatomical and chemical characteristics of *Leucaena leucocephala* and its impact on pulp and paper making properties. *Journal of Scientific and Industrial Research*. 2004;**63**:125-133
- [12] Tutus A, Ezici AC, Ates S. Chemical, morphological and anatomical properties and evaluation of cotton stalks (*Gossypium hirsutum* L) in pulp industry. *Scientific Research and Essays*. 2010;**5**(12):1553-1560
- [13] He Z. Determination of Strength Properties of Norway Spruce after Sulphate Cooking and Oxygen Delignification. *Saimaa University*; 2011 Retrieved from <http://publications.theseus.fi/handle/10024/30125>
- [14] Laftah WA, Wan Abdul Rahman WA. Pulping process and the potential of using non-wood pineapple leaves fiber for pulp and paper production: A review. *Journal of Natural Fibers*. 2016;**13**(1):85-102
- [15] Yang H, Chen D, van de Ven TG. Preparation and characterization of sterically stabilized nanocrystalline cellulose obtained by periodate oxidation of cellulose fibers. *Cellulose*. 2015;**22**(3):1743-1752
- [16] Gharekhani S, Sadeghinezhad E, Kazi SN, Yarmand H, Badarudin A, Safaei MR, Zubir MNM. Basic effects of pulp refining on fiber properties—A review. *Carbohydrate Polymers*. 2015;**115**:785-803
- [17] Deniz I, Ates S. Determination of optimum kraft pulping conditions using bamboo (*Pyllotachys bambusoides*). In: 2nd National Black Sea Forestry Congress Proceedings. Artvin, Turkey; 2002
- [18] Tutus A, Eroglu H. An alternative solution to the silica problem in wheat straw pulping. *Appita Journal*. 2004;**57**(3):214-217
- [19] Tutus A, Ates S, Deniz I. Pulp and paper production from spruce wood with Kraft and modified Kraft methods. *African Journal of Biotechnology*. 2010;**9**(11):1648-1654
- [20] Marklein AR, Winbourne JB, Enders SK, Gonzalez DJ, Huysen TL, Izquierdo JE, Norton RA. Mineralization ratios of nitrogen and phosphorus from decomposing litter in temperate versus tropical forests. *Global Ecology and Biogeography*. 2016;**25**(3):335-346
- [21] Stoklosa RJ, Hodge DB. Fractionation and improved enzymatic deconstruction of hardwoods with alkaline delignification. *Bioenergy Research*. 2015;**8**(3):1224-1234

- [22] Vargas González F, González Z, Rojas O, Garrote G, Rodríguez Pascual A. Barley straw (*Hordeumvulgare*) as a supplementary raw material for *Eucalyptus camaldulensis* and *pinussylvestris* kraft pulp in the paper industry. 2015
- [23] Liese W, Tang TKH. Properties of the bamboo culm. In: Bamboo. Springer International Publishing; 2015. pp. 227-256
- [24] Li Y, Liu X, Zhang S, Yao Y, Yao X, Xu J, Lu X. Dissolving process of a cellulose bunch in ionic liquids: A molecular dynamics study. *Physical Chemistry Chemical Physics*. 2015; **17**(27):17894-17905
- [25] Belle J, Odermatt J. Initial wet web strength of paper. *Cellulose*. 2016;**23**(4):2249-2272
- [26] Olejnik K, Stanislawska A, Wysocka-Robak A. Properties of natural cellulose fibers and methods of their modification for the purpose of paper quality improvement. In: *Handbook of Sustainable Polymers: Structure and Chemistry*. Wolczanska, Lodz, Poland: Institute of Papermaking and Printing, Lodz University of Technology; 2016. p. 19
- [27] Yazawa K, Ishida K, Masunaga H, Hikima T, Numata K. Influence of water content on the β -sheet formation, thermal stability, water removal, and mechanical properties of silk materials. *Biomacromolecules*. 2016;**17**(3):1057-1066
- [28] Yuan Z, Kapu NS, Beatson R, Chang XF, Martinez DM. Effect of alkaline pre-extraction of hemicelluloses and silica on Kraft pulping of bamboo (*Neosinocalamusaffinis*Keng). *Industrial Crops and Products*. 2016;**91**:66-75
- [29] Yuan Z, Wen Y, Kapu NS, Beatson R, Martinez DM. A biorefinery scheme to fractionate bamboo into high-grade dissolving pulp and ethanol. *Biotechnology for Biofuels*. 2017;**10**(1):38
- [30] Taflick T, Schwendler LA, Rosa SM, Bica CI, Nachtigall SM. Cellulose nanocrystals from acacia bark–influence of solvent extraction. *International Journal of Biological Macromolecules*. 2017;**101**:553-561
- [31] Mishra S, Mohanty AK, Drzal LT, Misra M, Hinrichsen G. A review on pineapple leaf fibers, sisal fibers and their biocomposites. *Macromolecular Materials and Engineering*. 2014;**289**:955-974
- [32] Yuan Z, Kapu NS, Beatson R, Chang XF, Martinez DM. Effect of alkaline pre-extraction of hemicelluloses and silica on kraft pulping of bamboo (*Neosinocalamusaffinis*Keng). *Industrial Crops and Products*. 2016;**91**:66-75
- [33] Bilal M, Iqbal HM, Hu H, Wang W, Zhang X. Metabolic engineering and enzyme-mediated processing: A biotechnological venture towards biofuel production—a review. *Renewable and Sustainable Energy Reviews*. 2018;**82**:436-447
- [34] Bajpai P. *Pulp and Paper Industry: Chemicals*. Elsevier; 2015
- [35] Laftah WA, Wan Abdul Rahman WA. Pulping process and the potential of using non-wood pineapple leaves fiber for pulp and paper production: A review. *Journal of Natural Fibers*. 2016;**13**(1):85-102

- [36] Upton BM, Kasko AM. Strategies for the conversion of lignin to high-value polymeric materials: Review and perspective. *Chemical Reviews*. 2015;**116**(4):2275-2306
- [37] Patt R, Kordsachia O. Herstellung von Zellstoffen unter Verwendung von alkalischen Sulfitlosungen mit Zusatz von Anthrachinon und Methanol. *Papier*. 1986;**40**(10A):V1-V8
- [38] Young RA, Akhtar M. *Environmentally Friendly Technologies for the Pulp and Paper Industry*. John Wiley & Sons, Inc; 1998
- [39] Kautto J. Evaluation of two Pulping-Based Biorefinery Concepts. *Acta Universitatis Lappeenrantaensis*; 2017
- [40] Alekhina M, Ershova O, Ebert A, Heikkinen S, Sixta H. Softwood Kraft lignin for value-added applications: Fractionation and structural characterization. *Industrial Crops and Products*. 2015;**66**:220-228
- [41] Yang X, Li N, Lin X, Pan X, Zhou Y. Selective cleavage of the aryl ether bonds in lignin for depolymerization by acidic lithium bromide molten salt hydrate under mild conditions. *Journal of Agricultural and Food Chemistry*. 2016;**64**(44):8379-8387
- [42] Moradbak A, Tahir PM, Mohamed AZ, Peng LC, Halis R. Effects of alkaline sulfiteanthraquinone and methanol pulping conditions on the mechanical and optical paper properties of bamboo (*Gigantochloa scortechinii*). *BioResources*. 2016;**11**(3):5994-6005
- [43] Kaur D, Bhardwaj NK, Lohchab RK. A study on pulping of rice straw and impact of incorporation of chlorine dioxide during bleaching on pulp properties and effluents characteristics. *Journal of Cleaner Production*. 2018;**170**:174-182
- [44] Singh R, Krishna BB, Kumar J, Bhaskar T. Opportunities for utilization of non-conventional energy sources for biomass pretreatment. *Bioresource Technology*. 2016;**199**:398-407
- [45] Bhutto AW, Qureshi K, Harijan K, Abro R, Abbas T, Bazmi AA, Yu G. Insight into progress in pre-treatment of lignocellulosic biomass. *Energy*. 2017;**122**:724-745
- [46] Wang S, Ru B, Lin H, Sun W, Luo Z. Pyrolysis behaviors of four lignin polymers isolated from the same pine wood. *Bioresource Technology*. 2015;**182**:120-127
- [47] Owolabi AWT, Arniza G, wan Daud W, Alkharkhi AF. Effect of alkaline peroxide pretreatment on microfibrillated cellulose from oil palm fronds rachis amenable for pulp and paper and bio-composite production. *BioResources*. 2016;**11**(2):3013-3026
- [48] Zhao X, Cheng K, Liu D. Organosolvpretreatment of lignocellulosic biomass for enzymatic hydrolysis. *Applied Microbiology and Biotechnology*. 2009;**82**(5):815
- [49] Lehto JT, Alén RJ. Chemical pretreatments of wood chips prior to alkaline pulping-a review of pretreatment alternatives, chemical aspects of the resulting liquors, and pulping outcomes. *BioResources*. 2015;**10**(4):8604-8656
- [50] Sridach W. The environmentally benign pulping process of non-wood fibers. *Suranaree Journal of Science and Technology*. 2010;**17**(2)

- [51] Korotkova E, Pranovich A, Wärnå J, Salmi T, Murzin DY, Willför S. Lignin isolation from spruce wood with low concentration aqueous alkali at high temperature and pressure: Influence of hot-water pre-extraction. *Green Chemistry*. 2015;**17**(11):5058-5068
- [52] Patt R, Kordsachia O. Anforderungen an neue Zellstoffherstellungsverfahren. *Wochenblatt für Papierfabrikation*. 1988;**116**(7):709-713
- [53] Razalli RL, Abdi MM, Tahir PM, Moradbak A, Sulaiman Y, Heng LY. Polyaniline-modified nanocellulose prepared from Semantan bamboo by chemical polymerization: Preparation and characterization. *RSC Advances*. 2017;**7**(41):25191-25198
- [54] Khristova P, Kordsachia O, Patt R, Khider T, Karrar I. Alkaline pulping with additives of kenaf from Sudan. *Industrial Crops and Products*. 2002;**15**(3):229-235
- [55] Jahan MS, Chowdhury DAN, Islam MK. ASAM Pulping of Jute. *Pulp & Paper Science and Technology. Alternative Papermaking Fibres*; 2003. pp. 252-258
- [56] Kordsachia O, Wandinger B, Patt R. Some investigations on ASAM pulping and chlorine free bleaching of eucalyptus from Spain. *HolzAlsRoh-Und Werkstoff*. 1992;**50**(3):85-91
- [57] Mertoglu-Elmas G, Gunaydin K, Ozden O. Environmental friendly alkaline sulfiteanthraquinone-methonal (ASAM) pulping with Rumexcrispus plant extract of woody materials. *Journal of Environmental Biology*. 2012;**33**(5):941-944
- [58] Gominho J, Lopes C, Lourenço A, Simões R, Pereira H. Eucalyptus globulus stumpwood as a raw material for pulping. *BioResources*. 2014;**9**(3):4038-4049
- [59] Jahan MS, Rubaiyat A, Sabina R. Evaluation of cooking processes for Tremaorientalis pulping. *Journal of Scientific and Industrial Research*. 2007;**66**(10):853-859
- [60] Derrien E, Marion P, Pinel C, Besson M. Influence of residues contained in softwood hemicellulose hydrolysates on the catalytic oxidation of glucose to glucarate in alkaline aqueous solution. *Organic Process Research and Development*. 2016;**20**(7):1265-1275