

FUTURE CELLULOSE BASED INDUSTRIES IN BANGLADESH –
A MINI REVIEW

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Lignocellulosic products can contribute to a low carbon economy, which can support in achieving the sustainable development goals of a country. The demand for pulp and paper in the developing world is constantly increasing. Due to environmental awareness, interest in bio-based products is mounting, encouraging the establishment of integrated biorefineries.

Bangladesh is facing an acute shortage of fibrous raw materials, as forest resources are limited. This paper provides an overview of the characteristics of raw materials that would be available for pulping to future pulp industries in Bangladesh. Rice straw is the most abundant raw material in Bangladesh, followed by wheat straw. However, both rice and wheat straws contain a very high amount of silica, which restricts their use in pulping. An alternative technology has been developed to overcome the drawbacks of non-wood pulping, where all dissolved biomass fractions are used in the development of bio-based products.

Keywords: non-wood, α -cellulose, fibre length, pulping, papermaking properties, biorefinery

INTRODUCTION

Bangladesh is a land scarce South Asian country, with a lack of forest resources. It has only about 11% forest land,^{1,2} with a high population density. However, from this aforementioned forest resource, a large portion is preserved, where wood cannot be exploited. Because of lack of wood resources, all the virgin pulp mills are out of production in Bangladesh. At present, the country has a paper production capacity of 1.5 million MT, which is based on recycled paper and imported pulp. Bangladesh imported 418772 MT of chemical wood pulp for paper production, with the expenses of US\$ 262.299 million in 2018.³ The per capita paper consumption in Bangladesh is about 3.4 kg, whereas in advanced countries its almost 250 kg and the world average per capita consumption is 55 kg. However, in Asia, the average per capita consumption is 44 kg, which contributes to 45%

of the total amount of paper produced in the world.⁴ Karnaphuli Paper Mill (KPM) is the largest government-owned integrated pulp and paper mill in Bangladesh using bamboo and gamari wood as raw materials,⁵ from the Chittagong Hill Tracts forests. Recently though, KPM has also become dependent on imported pulp and recycled paper, because of inadequate supply of fibrous raw materials.

The GDP growth rate in Bangladesh has consistently been above 6 for the past 12 years, with the exception of years 2009-2010, which has consequently raised the living standard of people. The demand for consumer products has therefore increased as well. The paper consumption in Bangladesh has also increased correspondingly with the GDP growth, thereby, alternative fibrous raw materials are needed to meet the increasing paper demands.

In Bangladesh, the available raw materials for papermaking are short fibred hardwoods, agricultural wastes, industrial crops and recycled pulp.⁶ To meet the balance between the increasing demand for lignocellulose-based raw materials and the scarcity of forest land, investigations on fast-growing species, as well as on the suitability of non-wood fibre for pulp and cellulose industries, have been intensified. The most potential fast-growing species in Bangladesh is *Trema orientalis*, which is an underutilized native species. Research results have shown that *Trema orientalis* is promising for pulp production.^{7,8} As a native species, it is well acclimated to the Bangladeshi climate and is able to grow everywhere in the country. Bangladesh has 44000 ha of allocated forest land for social forestry, which can be utilized for the plantation of *T. orientalis* without affecting natural forests and the environment.

Also, considering that Bangladesh is an agricultural country, significant amounts of agricultural wastes are generated every year, which could be a potential source for pulp production. From these wastes, approximately 2.5 billion tons per year⁹ are non-wood fibrous materials suitable for papermaking, which would produce almost 10 million tons of pulp. About 6% of the world's pulp comes from non-wood materials.¹⁰ Most of the non-wood pulp is produced from straw (44.4%), bagasse (14.3%), reed (14.3%), bamboo (21.43%), and the rest from other types of biomass (5.6%).¹¹ The major portion of non-wood pulp is produced in China and India.¹² In 2013, approximately 53% of the world's non-wood fibre was produced in China,¹³ which is 39% of the total Chinese national pulp production.¹⁴ Non-wood biomass has lower lignin content, compared to wood, and is generally easier to delignify, as it has lower activation energy.¹⁵ Non-wood fibres are derived from selected tissues of various mono- or dicotyledonous plants and are categorized botanically as grass, bast, leaf or fruit fibres.¹⁷ Non-wood pulps can be grouped into two broad categories, according to their fibre length,¹⁸ such as short fibre and long fibre.

For environmental considerations, nowadays, non-wood pulping is encouraging. Moreover, some non-wood plants even give higher yield of pulp per hectare than wood.¹⁶ However, non-wood pulping also has some limitations and disadvantages. For instance, a large number of non-wood plants contain high amounts of silica

and fines,^{19,20} which are undesirable components for pulping. Other important drawbacks of non-wood materials include the fact that they are highly localized resources and their low density, which increase transportation costs.

In this review, the non-wood raw materials available for pulp production in Bangladesh are surveyed in terms of their morphological, chemical, pulping and papermaking properties. The integration of non-wood pulping into a biorefinery framework has also been addressed. In addition to non-woods, the possibility of *T. orientalis* pulping is also discussed.

CHEMICAL PROPERTIES OF AVAILABLE RESOURCES

The chemical characteristics of native fast-growing wood and non-wood species in Bangladesh vary considerably due to geographical variation, along with soil and weather conditions (Table 1).

The cellulose content in raw materials is known to positively influence pulp yield during chemical pulping and also has a profound effect on paper strength.^{35,36} Lignocellulosic materials that contain 34% or more α -cellulose content are considered suitable for pulping and paper manufacturing.²² Among non-woods, bast fibre, like jute and okra fibres, has the highest amount of α -cellulose, even though the α -cellulose content of most of the non-woods is lower than that of hardwoods (Table 1). However, harvesting time and geographical locations significantly affect the morphology and chemical composition of non-woods. As shown in Table 1, the α -cellulose content in wheat straw was 40.1%, while in another study it was 37.0%.³⁸ Similarly, the α -cellulose content in bagasse was reported as 41.3% (Table 1), which was lower than the α -cellulose content in whole bagasse characterized by Andrade *et al.*³⁹

In the process of chemical pulping, a certain amount of hemicelluloses is dissolved in cooking liquor and the remaining substantial quantity of hemicelluloses persists within the pulp, which induces swelling of the pulp fibre.³³ Hemicelluloses play an important role in bonding, which influences papermaking properties. Although increased hemicellulose content within the pulp increases the tensile strength of paper, it decreases the tearing resistance and fold endurance.³⁴ The maximum burst strength has been obtained at about 15% alkali-extractable hemicellulose content.²³ Xylan is the main

hemicellulosic oligomer present in non-wood hemicelluloses, and it is reflected in the pentosan content.

When considering pulping, lignin is an undesirable component of lignocellulosic biomass. It is removed during the pulping process performed to defibrate the raw material. Lower lignin content in the raw materials is suitable for delignification under mild pulping conditions, with lower energy consumption and lower chemical load, to reach a desirable kappa number. As shown in Table 1, the lignin content in most of the non-woods is lower than that of *Trema orientalis*, a native fast-growing hardwood species found in Bangladesh. However, the lignin content in some non-wood plants, such as bamboo, dhaincha, okra stick *etc.*, is similar to that of hardwoods. The lignin content in jute fibre is very low, when compared to other non-woods and hardwoods.³⁷

Other undesirable elements are extraneous components, such as tannins, gums, sugars, inorganic matter and coloured compounds, present within biomass. These can be partially removed with cold water treatment; additionally, hot water treatment can remove starches. Therefore, a major factor that needs to be taken into account is their high water solubility.²¹ Some non-woods, such as rice straws, wheat straws, corn stalks, *Cyperus flabelliformis etc.*, have very high water and alkali soluble extractives. For example, *C. flabelliformis* has been found to have hot water solubility (HWS) of 25.9% and cold water solubility (CWS) of 23.4%²² (Table 1). On the other hand, the water and alkali solubility of dhaincha (*Sesbania bispinosa*),²³ okra fibre,²⁴ *etc.* is similar to that of some wood species, such as *Trema orientalis*.⁷ A chemical property that affects adversely the paper machine runnability of pulp is the extractives solubility in acetone and DMC. Banana stem showed high extractive content (3.25%) in acetone²⁵ (Table 1). The higher content of extractives is an undesirable property for pulping, bleaching and papermaking as it degrades the quality of paper.²¹ Alkali solubility provides information about cooking conditions. Values higher than one percent alkali solubility indicate mild cooking conditions and may provide satisfactory results, producing pulp of acceptable quality.²²

Another important characteristic of non-woods is their high amount of ash, which represents the mineral content in biomass. It is known that the most common minerals in ash are Mn, Fe and Cu.

The ash contents of non-wood plants vary between 1% and 20%, whereas in softwoods and hardwoods the ash is generally less than 1%. Hence, there are no recovery problems associated with silica in wood pulping,⁴⁰ while some 65 to 70% of the cereal straw ash is silica-related. Tutus and Eroglu (2004) investigated soda-oxygen anthraquinone (SOAQ) pulping of wheat straw and found that 88.4% of the silica remained in the pulp with this process.⁴¹ In this study, the oxide-added SOAQ pulping process was used to further enhance silica precipitation on pulp by adding 1 to 3% oxide, such as Al₂O₃, CaO and MgO. It was found that the oxide-added SOAQ process increased silica precipitation on pulp by about 9%, compared to the SOAQ pulping process. Oxide-added SOAQ pulp showed good physical and optical properties as well. However, the method did not describe process economics. In the organic acid pulping process, silica effectively retained on the pulp fibre, thereby, making solvent recovery easier. Therefore, an organosolv system is advantageous for non-wood pulping. Higher ash content in the raw material creates problems in chemical recovery, bleachability,⁴² and strength of paper.

Thus, besides *T. orientalis*, non-woods such as dhaincha, kash, rice straw, bagasse, bamboo *etc.* can be used for pulping (Table 1). However, the processing of these non-woods will require alternative technologies for pulping.

As shown in Figure 1, many non-woods, such as straw, corn stalk, banana stalk, *C. flabelliformis etc.*, are anatomically loosely bonded. The fibres present in vascular bundles are surrounded by parenchymatic cells, which are the source of primary fines. The fines in non-wood pulps increase water retention, which slows down the paper machine speed. Such non-wood resources have a lower cooking temperature and could be suitable for handmade paper.⁴³ The non-fibrous parenchymatic cells lead to the formation of many fines during the pulping process, hampering pulp washing, paper machine runnability and drying. Specifically, one of the major drawbacks in using bagasse for high quality pulp is the presence of pith, which adversely affects pulp yield and chemical consumption, also causing quality related problems. In order to resolve this issue, Jahan and co-authors prehydrolysed bagasse, corn stalks and *Saccharum spontaneum*, prior to pulping, in an integrated biorefinery concept.^{44,45}

Table 1
Chemical properties of different raw materials available in Bangladesh

Samples	Extractives (%)				Lignin (%)		Pentosan (%)	Holo-cellulose (%)	α -cellulose (%)	Ash (%)	Reference	
	DMC	Acetone	HWS	CWS	1% Alkali	Klason						Acid soluble
Dhaincha	-	0.37	3.76	-	20.00	23.191	-	16.02	66.10	39.74	1.60	23
<i>C. flabelliformic</i>	-	1.5	25.9	23.4	49.6	24.0	-	20.4	-	32.2	1.5	22
Rice straw	-	-	19.9	14.4	49.2	22.1	4.1	23.5	-	38.2	14.6	26
Rice straw	-	1.1	19.1	-	-	12.7	-	-	65.4	38.5	17.2	27
Wheat straw	-	0.9	-	-	-	15.0	-	21.9	65.6	40.1	9.7	27
Corn stalks	-	-	-	-	-	-	-	-	-	39.4	9.9	
Golpata	1.7	-	14.4	11.5	40.8	18.1	-	24.9	-	36.3	7.03	28
Banana stem	-	3.25	-	22.85	51.39	12.76	5.05	16.17	50.22	32.55	13.39	25
Kash	-	0.85	10.8	10.4	36.2	17.3	-	23.6	65.4	41.6	6.8	29
Bagasse	-	1.2	6.6	6.4	35.8	18.1	-	25.1	65.8	41.3	1.97	29
Okra stick	-	2.92	-	-	29.2	25.2	-	16.9	70.6	34.3	0.6	24
Okra fibre	-	1.5	-	-	17.3	12.6	-	17.8	85.9	56.7	2.0	24
Bamboo	-	-	-	-	-	25.5	-	24.2	-	45.2	2.2	30
Pati	1.4	-	12.7	-	39.1	16.8	-	33.6	71.0	34.4	3.7	31
<i>A. auriculiformis</i>	-	-	-	3.2	27.9	19.4	-	17.5	76.1	44.1	0.6	32
<i>T. orientalis</i>	-	0.89	4.9	2.4	21.4	24.1	2.8	23.5	78.5	45.0	1.1	7

*HWS = Hot water solubility; AS = Alkali solubility; Extractive content in acetone, DCM = Dichloromethane

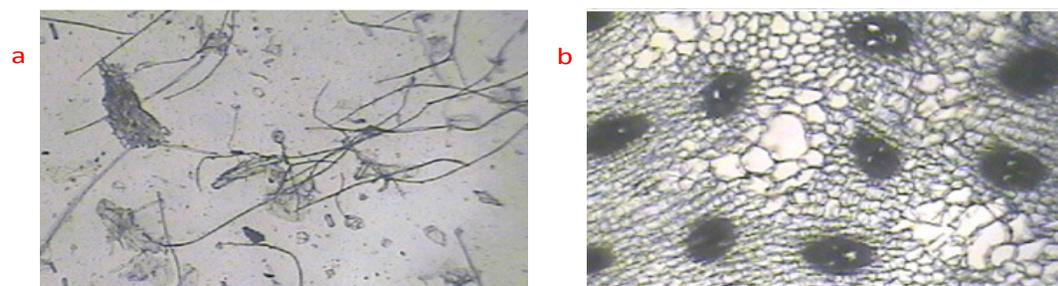


Figure 1: a) Macerated fibre, b) Cross-section of *C. flabelliformic*²²

Table 2
Physical and morphological properties of raw materials

Raw material	Density, g/cm ³	Fibre length, mm	Fibre width, µm	Slenderness ratio	Reference
Golpata	-	1.73	10	173.0	28
Banana stem	-	2.21	22.2	99.5	25
Kash	-	1.23	19.0	64.7	29
Bagasse	-	1.01	17.1	59.1	29
Okra stick	-	0.63	15.4	40.9	24
Okra fibre	-	3.0	13.4	223.9	24
<i>C. flabelliformis</i>	-	0.94	8.4	111.9	29
Jute fibre	-	2.5	19	131.6	6
Bamboo	0.84	2.1	24.4	86.1	30
Pati	-	1.3	12	108.3	31
<i>T. orientalis</i>	0.37	1.34	24.5	54.7	7
<i>A. auriculiformis</i>	0.57	1.1	20.6	53.4	32

Prehydrolysis of raw materials removes part of the fines and improves drainage resistance. At the same time, pre-extraction/prehydrolysis removes a considerable amount of lignin, hemicelluloses and acetic acid, which could be further used in producing biofuels, biochemicals and biomaterials. Therefore, the integrated biorefinery of some non-woods could solve the inherent problems related to conventional alkaline pulping of non-woods.

PHYSICAL AND MORPHOLOGICAL PROPERTIES

Physical and morphological properties of raw materials, such as density, fibre length and fibre width, have substantial effects on pulping and papermaking. The density of raw materials is one of the major parameters in assessing raw material quality for pulping. Most non-woods are bulky in nature. A raw material with high density is desirable for better use of digester capacity.³⁰ Goyal and co-authors⁴⁶ showed that, for 0.01 g/cc higher specific density, a eucalyptus clone produced 2 tons higher pulp yield in a digester of 4000 ft³. Table 2 shows the specific density of bamboo (0.84 g/cc) – the prevailing raw material used in KPM for pulping – which is higher than that of hardwood. The packing density of most of the non-woods is low; consequently, the digester yield is lower for non-woods. On the other hand, the total number of truck-miles to supply a fibrous raw material to a mill is substantially higher than that of wood chips. In support of non-wood pulping, practical considerations of raw material transportation need to be made, as

the mill size is usually much smaller than in the case of wood pulp operations.

A higher fibre length leads to higher tearing strength of paper.^{47,48} Much stronger paper can be produced from longer fibred pulps.³⁰ As can be seen from Table 2, the fibre length of most of non-wood plants is close to that of hardwood. The fibre length of jute, okra, banana *etc.* is longer and similar to that of softwoods, although the stick versions of jute stick and okra *etc.*²⁴ have shorter fibre length.²⁵ Fibre flexibility, another important physical property depends on fibre diameter,²⁹ which contributes to the slenderness ratio (fibre length/fibre diameter), a high value of which can positively affect the papermaking properties. Generally, fibres would have poor strength in the case of the slenderness ratio below 70.⁴⁷ For example, the chemical properties of the mulberry plant are satisfactory as a pulping raw material,¹⁶ but its low slenderness ratio (29.5) indicates that it would produce very low strength paper. In this case, weaker pulp can be blended with pulp with longer fibres and higher slender ratio, or cooked with longer fibre raw material^{6,30} – an idea that has been carried out in several studies. To achieve such reinforcement and obtain increased tensile, tear and burst strength, *T. orientalis* pulp has been combined with jute pulp.⁶ Jahan and Farouqui also showed that jute pulp reinforcement enhanced the papermaking properties of cotton stalk pulp.⁴⁹ Similarly, blending of the mulberry plant pulp with longer jute fibre pulp increased its tear index significantly.¹⁶

PULPING PROPERTIES

As shown in Table 3, non-woods, such as rice straw, wheat straw, bagasse, kash *etc.*, require lower temperature in conventional alkaline pulping, due to being anatomically loosely bonded and having lower lignin content. The raw materials easily reach a lower kappa number under mild cooking conditions. Kash also shows high screen pulp yield and low kappa number at only 16% alkali charge.²⁹ Bagasse can be another alternative raw material for pulping industries, as it has a high pulping yield and a lower kappa number.^{29,45,50} Researchers have already studied the potential of bagasse as a pulping raw material,⁵¹⁻⁵⁵ and it has already been used as a raw material at North Bengal Paper mill (NBPM). However, the decline of sugarcane farming resulted in a drop in the production of sugar mills, and thus the resulting by-product bagasse became insufficient for running a paper mill. As a consequence, NBPM is now out of production. In this situation, kash can be a potential supplementary raw material to be used at NBPM to put it back into operation. Using the kraft pulping process, the pulp yield from dhaincha was 43.72% with kappa number 10.0, which was quite acceptable, whereas the bamboo showed a pulp yield of 39.8% with kappa number 12.5 (Table 3).⁵⁶ Bamboo from the hill region in Bangladesh has been used as a pulping raw material at Karnaphuli Paper Mills.

There are some limitations of non-wood pulping using conventional alkaline processes, *e.g.* i) chemical recovery, ii) slow drainage and iii) bulky in nature. To overcome these problems, alternative pulping processes have been studied.^{27,38,60-62} Formic acid pulping of rice straw produced pulp yields of 50.4% and kappa number of 30.7%, which is quite high.⁵⁷ The silica content is the main problem for the rice and wheat straw pulping,^{26,60,63} but it can be solved by organic acid pulping.⁵⁷ The formic acid pulping of agricultural wastes is

well fit in an integrated biorefinery. The dissolved lignin and hemicelluloses can be easily separated and used for biofuels, biochemicals and biomaterials. The silica retained on pulp fibre in the organic acid pulping process can be dissolved in alkaline extraction, followed by precipitation. The separated lignin can also be used as a value-added product in an integrated biorefinery. A detailed description of this valorisation possibility has been given by Sutradhar *et al.*⁶⁴ Organic acid lignin is characterized by low content of methoxyl groups and high content of phenolic hydroxyl groups. This lignin can replace 40% phenol in phenol-formaldehyde resin preparation.⁶⁵ The dissolved hemicelluloses can then be converted to furfural⁶⁶ and biochemicals⁶⁷ (Scheme 1a).

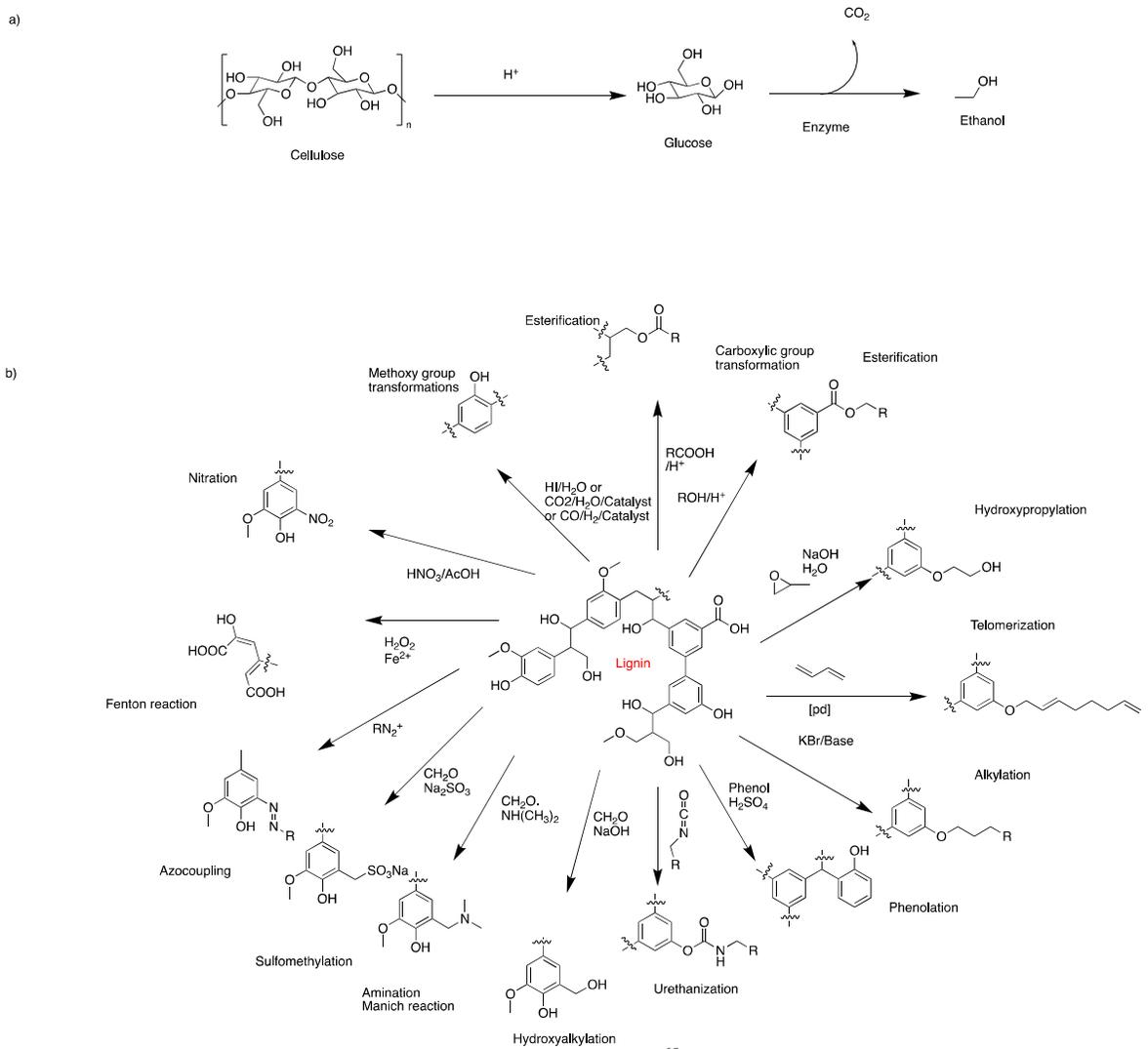
Using potassium hydroxide alone, or with aqueous ammonia, as pulping liquor (again, the idea is to use the spent liquor as fertilizer) is one of the attempts for environmentally friendly pulping processes (Scheme 2). Huang *et al.* investigated wheat straw pulping using aqueous ammonia mixed with caustic potash as cooking liquor.⁷¹ They recovered excess free ammonia by distillation and reused it in batch pulping. They recovered about 98% free ammonia in the distillation process. After distillation, the concentrated black liquor was treated with aluminium polychloride and polyacrylamide for flocculation of the dissolved biomass and separated. The supernatant was further reused four times as cooking liquor by adding extra NH₄OH and KOH. The amount of delignification and the pulp yield of the process remained steady at 82-85% and 48-50%, respectively, while reusing the supernatant four times. The final potassium containing supernatant was used as fertilizer.

Sugarcane bagasse was subjected to pulping at 165 °C with a NH₄OH-KOH mixture in the presence of anthraquinone by Huang *et al.*⁷²

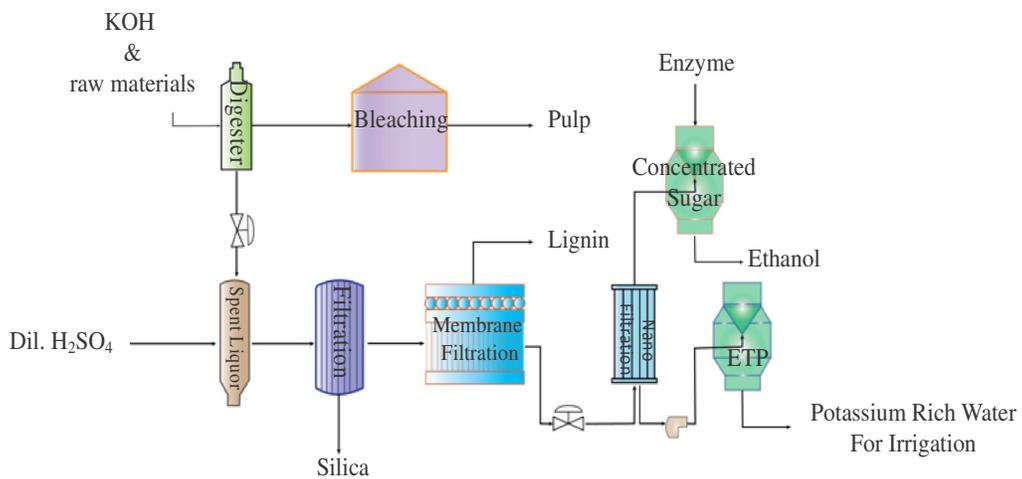
Table 3
Pulping of different non-woods by different processes

Samples	Chemical (%)	Time (min)	Temperature (°C)	Liquor:Material	Pulp yield (%)	Reject (%)	Kappa number	Reference
<i>Soda pulping</i>								
* <i>C. flabelliformis</i>	12	120	boiling	10:1	52.5	2.5	15.5	29
**Golpata	18	90	170	6:1	36.2	1.0	29.1	28
*Kash	14	120	150	6:1	52.6	-	18.3	29
*Bagasse	14	120	150	6:1	50.2	-	16.5	29
*** <i>T. orientalis</i>	20	120	170	4:1	49.0	0.0	17.6	8
[§] Pati	10	120	boiling	8:1	48.3	-	17.2	31
[§] Rice straw	12	120	150	1:6	41.1	0.0	10.8	27
[§] Wheat straw	12	120	150	1:6	48.2	0.0	16.9	
<i>Kraft pulping</i>								
Dhaincha	18	120	170	6:1	43.72	-	10.0	23
Bamboo	16	120	170	4:1	39.8	-	12.5	56
Golpata	18	90	170	6:1	37.2	-	27.2	28
<i>Formic acid pulping</i>								
Bagasse	90	120	95	10:1	43.9	-	25.6	50
Rice straw	85	120	80	10:1	50.4	-	30.7	57
Jute fibre	70	120	boiling	10:1	64.3	-	19.3	58
<i>Potassium hydroxide</i>								
Wheat straw			150	1:6	44.7	0.0	13.6	
Dhaincha			170	1:5	48.6	1.9	19.4	59
Jute stick			170	1:5	48.4	0.4	32.5	
Corn stalk			150	1:6	45.8	0.0	19.0	
Rice straw	12.8	120	150	1:6	42.4	0.0	10.3	27
Wheat straw	12.8	120	150	1:6	48	0.0	16.1	

*KOH pulping; **Soda-AQ (anthraquinone); ***4% Na₂CO₃ prehydrolysis, Soda-AQ; [§]NaO



Scheme 1: Biomass to chemicals, a) Pyrolysis of hemicelluloses,⁶⁸ b) Enzymatic conversion of cellulose to bioethanol,⁶⁹ b) Different pathways for chemical treatment of lignin⁷⁰



Scheme 2: Integrated biorefinery adopted at a pulp mill

The objective of this pulping process was to eliminate the black liquor problem in the traditional pulping process. The addition of anthraquinone greatly enhanced the delignification of bagasse. The pulping process was well suited for the cooking of bagasse, where the bagasse was delignified to a low kappa number of 11.3, the delignification and the pulp yield were 80% and 65%, respectively. They replicated the process on a pilot scale successfully and also demonstrated a degree of repeatability. At the same time, they also mentioned that the utilization of nitrogen, phosphorus, potassium and ammonia lignin rich black liquor as a fertilizer in agriculture could solve the problem associated with black liquor for the pulping industry. The conversion of black liquor into a fertilizer for agricultural use is the ultimate target in the potassium hydroxide pulping process of non-wood to overcome the black liquor recovery problem. Lignin and polysaccharides can be recovered and converted into valuable products. Sun *et al.* (1999) separated the dissolved biomasses from black liquor that were released after pulping palm oil trunk fibres with a potassium hydroxide-anthraquinone process.⁷³ They separated the lignin and polysaccharides in a two-step process. In the first step, the pH of the black liquor was reduced to 6 using phosphoric acid to precipitate the polysaccharides in ethanol, keeping the lignin in the filtrate. Then, the filtrate was concentrated by evaporation and reduced to a pH of 1.5 to fully precipitate the lignin. Finally, the liquor was neutralized using potassium hydroxide to be used as liquid fertilizer.

Jahan *et al.* (2016) produced pulp from rice straw using potassium hydroxide (KOH) as cooking liquor and compared it with the soda rice straw pulp.²⁷ The cooking conditions were: 150 °C for 2 h, KOH charge of 12% as NaOH, and material to liquor ratio of 1:6. The pulp yield was 42.4%, at the kappa number of 10.3. No significant differences in bleachability and papermaking properties of NaOH and KOH pulps were observed. The rice straw KOH pulp had 85% brightness after bleaching with ClO₂ of 25 kg/ton of pulp by the D₀(EP)D₁ bleaching sequences. They also separated silica and lignin by precipitation

from black liquor by dropping the pH using 0.2 M sulphuric acid from 7 to 2. Finally, the potassium rich supernatant was stored to be used as fertilizer. Rodríguez *et al.* (2008) also investigated rice straw as an alternative resource for producing paper grade pulp.⁶⁰ They produced pulp from rice straw in potassium hydroxide, soda and kraft processes. The pulping was carried out at 170 °C and 180 °C. The obtained soda rice straw pulp showed the best performance in terms of drainage index, breaking length, and stretch and burst indices.

Potassium hydroxide pulping was also investigated for dhaincha (*Sesbania bispinosa*), jute stick (*Corchorus capsularis*), wheat straw (*Triticum aestivum*) and corn stalks (*Zea mays*).⁵⁹ Dhaincha, wheat straw and corn stalks were delignified to kappa numbers of 19.4, 13.6 and 19, respectively, while jute stick did not get delignified sufficiently (kappa number 32.5). Pulp yields were quite high, compared to conventional soda processes, and showed good bleachability in D₀(EP)D₁ bleaching sequences and papermaking properties. Potassium hydroxide pulping was also proved to be a promising alternative for *Saccharum spontaneum* (kash) and bagasse (*Saccharum officinarum*).²⁹ The KOH spent liquor was used in soil amendment after separating the silica. KOH spent liquor lignin from rice straw was used in producing activated carbon by phosphoric acid (H₃PO₄) activation.⁷⁴ Like in organic acid pulping, the KOH pulping of non-wood also fits well within an integrated biorefinery, where silica, lignin and dissolved hemicelluloses can be separated for bio-based development and potassium rich liquor can be used in irrigation, as shown in Scheme 3.

PULP BLEACHING

The residual lignin is removed from the chemical pulp by bleaching. Nowadays, elemental chlorine free (ECF) and total chlorine free (TCF) bleaching processes are common practice in chemical pulp bleaching. TCF bleaching includes ozone, oxygen, peroxide *etc.* However, elemental chlorine is hazardous for the environment and therefore its use is discouraged. Still, pulp mills in Bangladesh are continually using elemental chlorine bleaching. Recently, an oxygen

delignification plant has been installed at KPM, which delignifies 30-50% of residual lignin, reducing the chlorine demand in bleaching.⁵ The instalment of an oxygen plant, prior to the chlorine bleaching plant, is also effective to reduce COD, BOD and the consumption of bleaching chemicals.^{75,76} The oxygen delignification stage releases the pressure on the bleaching plant, which is eco-friendly in achieving sustainable development goals.

Pulp bleachability varies among the raw materials. Jute fibre pulp showed excellent pulp bleachability in conventional DED (D: chlorine dioxide treatment, E: alkaline extraction treatment) bleaching. Jute fibre pulp reached 90.3% brightness using only 11 kg ClO₂/ton pulp.⁷⁷ Dhaincha is a fast-growing nitrogen fixing non-wood species grown in almost all parts of Bangladesh, which is used to increase the fertility of crop lands. Jahan and co-authors studied the pulpability of this species under varying conditions. The ISO brightness of dhaincha reached up to 83.1% after the D₀(EP)D₁ bleaching sequence (Table 4). Soda cooked rice straw pulp showed slightly lower brightness (80.3%), compared to potassium hydroxide cooked pulp (81.0%).²⁷ Unlike these, the woody materials of *T. orientalis* showed poor brightness (77.4%) using the D₀(EP)D₁ bleaching sequence.⁸ The bleachability of pulp also varied with the location of the raw material and the pulping processes. In DED bleaching, *T. orientalis* pulp from Dhaka region reached 84.1-84.9% brightness for the kraft process and 85.6-85.8% for the soda-AQ process, while the same plant from Gaybandha region reached 82.5-85.6% and 81.9-83.1%, respectively.⁷

Biotechnology has drawn considerable attention as an alternative to replace the toxic chlorine bleaching in the recent past. Biological bleaching with thermostable fungi and enzymes, *e.g.* xylanase,⁷⁸⁻⁸⁰ laccase,⁸¹⁻⁸⁴ hydrolases,^{85,86} has achieved promising results as an alternative for chlorine bleaching. Xylanase biobleaching has already been established as a potential environmentally friendly bleaching technique. Xylanase is especially used for the biobleaching of non-wood pulp.^{87,88} Wood pulp bleaching with xylanase also gives reduced (20%) kappa number,⁸⁹ and improved brightness⁹⁰ of kraft pulps. Xylanase pretreatment of pulp reduces by about 25% the consumption of bleaching

chemicals.^{79,91} Xylanase, a specific xylan-attacking enzyme, is now commercially used in pulp mills for bleaching.⁹² Jahan and co-researchers investigated xylanase for bleaching different *T. orientalis* pulps and noticed better brightness (76.6-88.6%).⁹³ However, some enzymes could readily attack cellulose and consequently reduce fibre strength.

In addition to pulp bleaching, enzymes have been used in different other steps of pulping and papermaking processes. For example, certain saprophytic organisms are able to degrade lignin by the use of an enzymatic cocktail. Laccases have been found to play a major role during lignin degradation and have therefore been intensively researched with regard to potential applications for biomass processing. Laccases can assist the pretreatment of biomass and promote the subsequent enzymatic hydrolysis of cellulose by the oxidative modification of residual lignin on the biomass surface.⁹⁴

Lipases have been able to hydrolyze triglycerides present in the pulp and prevent pitch deposition,⁹⁵ which has contributed to the recent progress and general status of the lipase pitch control technology in Japan.⁹⁵ The improvement of pulp drainage with enzymes has been practiced routinely at mill scale in different countries. Gil *et al.* evaluated cellulases and beta-glucanases for energy savings in the bleached *Eucalyptus globulus* kraft pulp refining process. This treatment improved pulp drainability by up to 80% at the same level of refining energy (1500 PFI revolutions).⁹⁶

Enzymatic deinking has also been successfully applied during mill trials and can be expected to expand in application as increasing amounts of newsprint must be deinked and recycled. The enzymatic deinking using cellulase and hemicellulase of laser printed waste papers was studied by Lee *et al.*,⁹⁷ who found an effective method for paper recycling, with an efficiency of about 73%.

Pre-extraction of hemicelluloses might also help to get desirable brightness with reduced consumption of bleaching chemicals. Jahan and co-authors introduced sodium carbonate pre-extraction of hemicelluloses for paper grade pulp of *T. orientalis* and observed better brightness (83.8%).⁸

PAPERMAKING PROPERTIES

The papermaking properties of bleached and unbleached pulps, produced from some wood and non-wood plants, as well as their specific drainage resistance, are shown in Table 4. Dhaincha pulp showed good papermaking properties, with a tensile index of 69.1 N.m/g, tear index of 8.8 mN.m²/g and burst index of 5.6 kPa.m²/g at 55 °SR²³. Kash pulp also showed good papermaking properties, and can be a supplementary raw

material for bagasse-based pulp mills in Bangladesh, as discussed above. As shown in Table 3, the tear index of jute fibre pulp was very high in a soda-AQ process. Shafi *et al.* showed that the NS-AQ process gave the best results in terms of pulp yield and papermaking properties.⁹⁸ The physical properties of NS-AQ pulps were also better than those of soda-AQ and AS-AQ pulps.⁹⁹

Table 4
Papermaking properties

Samples	Bleaching yield (%)	Brightness (%)	°SR (2000 Rev)	Tear index (mN.m ² /g)	Tensile index (N.m/g)	Burst index (kPa.m ² /g)	Reference
<i>Bleached (D₀(EP)D₁)</i>							
Dhaincha	93.97	83.1	55	8.8	69.1	5.6	23
Jute fibre	-	81.6	46	28.1	40.3	5.0	37
Bagasse	-	83.1	-	7.3	-	4.1	50
Bagasse	-	81.0	-	6.8	65.4	5.2	29
Kash	-	82.0	-	7.4	60.9	4.9	29
Okra	-	82.1	54	8.6	58.2	4.4	24
<i>T. orientalis</i>	-	73.4	-	8.1	33.6	2.3	8
Jute fibre**	-	81.5	-	-	-	-	58
Wheat straw	90.1	81.3	47	9.0	60.0	3.6	59
Wheat straw [§]	-	84.0	40	7.0	62.8	5.3	27
Rice straw [§]	-	81.0	40	6.8	38.4	2.9	
<i>Unbleached</i>							
<i>C. flabelliformic</i> *	-	-	47	11.4	59.9	4.4	22
Bagasse	-	-	-	7.8	-	3.2	50
Bamboo	-	23.2	-	17.8	24.8	2.1	56
Golpata*	-	-	40	11.6	-	4.5	28
<i>T. orientalis</i>	-	13.5	-	8.6	42.0	2.2	8
Rice straw	-	-	40	9.1	57	3.3	57
Pati*	-	-	45	12.3	-	3.5	31
Jute fibre	-	37.2	45	28.3	42.7	5.1	37

*Unbeaten, **Alkaline peroxide bleaching, [§]KOH pulping

At °SR 44, the tensile index of NS-AQ pulp was about 100 N.m/g for jute cuttings and 70 N.m/g for jute caddis, while their tear index was almost similar. The tear index of jute pulp was also very similar to that of softwood pulp.¹⁰⁰

The unbleached paper strength of *C. flabelliformic* is suitable for packaging industries,²² with a tensile index of 59.9 N.m/g, due to its long fibre and high slender ratio (Table 2). The drainage resistance of *C. flabelliformic* is also very high (47, unbeaten), compared to other conventional non-wood raw materials. Therefore, handmade paper could be produced from *C. flabelliformic* grass for packaging industries.

FUTURE PULPING IN BANGLADESH Fast-growing species

Trema orientalis is a native fast-growing species and grows everywhere in Bangladesh. A lot of studies^{6-8,36,39,101-106} have been carried out on the pulping behaviour, chemistry and anatomy of *T. orientalis* within the Pulp and Paper Research Division of BCSIR. *T. orientalis* possesses comparatively higher α -cellulose content (45%)⁷ than that of acacia trees (44.1%).³² Jahan and co-authors reported obtaining a screened pulp yield from *T. orientalis* of 49%, with kappa number 17.6, at the alkali charge of 20% in the soda-AQ process. In the D₀(EP)D₁ bleaching sequence, the pulp showed a tear index of 8.4 mNm²/g,

tensile index of 25.8 Nm/g and brightness of 77.4%.⁸ Kraft pulping decreases the pulp yield (43.5%), however, it increases the tensile index (43.5 Nm/g) and brightness (80.6%).³⁰ Recently, a test plantation scheme of *T. orientalis* has been assessed by BCSIR, with the collaboration of the Forest Department, Bangladesh, to check its potential for replacing acacia in the social forestry program. The papermaking properties of *T. orientalis* are comparable with those of many other fast-growing species in Bangladesh, and thus, it could be a potential raw material source for the cellulose industry. *T. orientalis* has similar papermaking properties to those of bamboo, which is used at KPM at present. The papermaking properties of *T. orientalis* are satisfactory for printing paper, and it can, therefore, be explored as an alternative raw material source to be used at KPM.

Acacia is an exotic fast-growing species, which has been planted in participatory forestry, agroforestry, roadside plantation and government land in all parts of the country. The species yields good α -cellulose content (44.1%) and low lignin content (19.4%),³² which are desired properties for pulping raw materials.

Agricultural wastes

The main crops cultivated in Bangladesh are rice, wheat, lentil, rapeseed and jute. Every year, rice grows on almost 10.5 million hectares of farmland. Wheat, the second staple food in Bangladesh, has been grown sporadically across the country on almost 0.35 million hectares of land, generating substantial amounts of crop residues. Another cash crop, jute, is grown on almost 0.62 million hectares of land per year. The rice and wheat straws and jute stick are currently being used for cattle feed, domestic fuel, fencing *etc.* to a limited extent. These have almost negligible economic value to the farmers. The characteristics and pulpability of these agricultural wastes have already been discussed in an earlier section. Technically and economically, pulp production from agricultural wastes is difficult to be performed by the conventional pulping processes because the raw materials i) are bulky in nature and scattered in location causing collection difficulties, ii) have high silica content, creating problems in chemical recovery, and iii) have high fines/pith content, causing slow

dewatering. To overcome these problems, alternative pulping processes are proposed, such as i) a small-scale KOH based pulp mills without chemical recovery, and ii) small-scale organic acid pulping with a recovery system. Both these options integrate well within the biorefinery concept.

The agricultural wastes transportation problem could be mitigated by introducing the concept of community-based social pulping (Scheme 3). Within this concept, small entrepreneurs will produce pulp in small-scale pulp mills and finally, the pulp will be supplied to a large-scale paper/bio-based mill for producing paper and bio-based products. This will involve both farmers and small entrepreneurs, and at the same time, will contribute to money circulation. Therefore, farmers, entrepreneurs and the industry will be the beneficiaries of such a project.

NON-WOOD BIOREFINERY

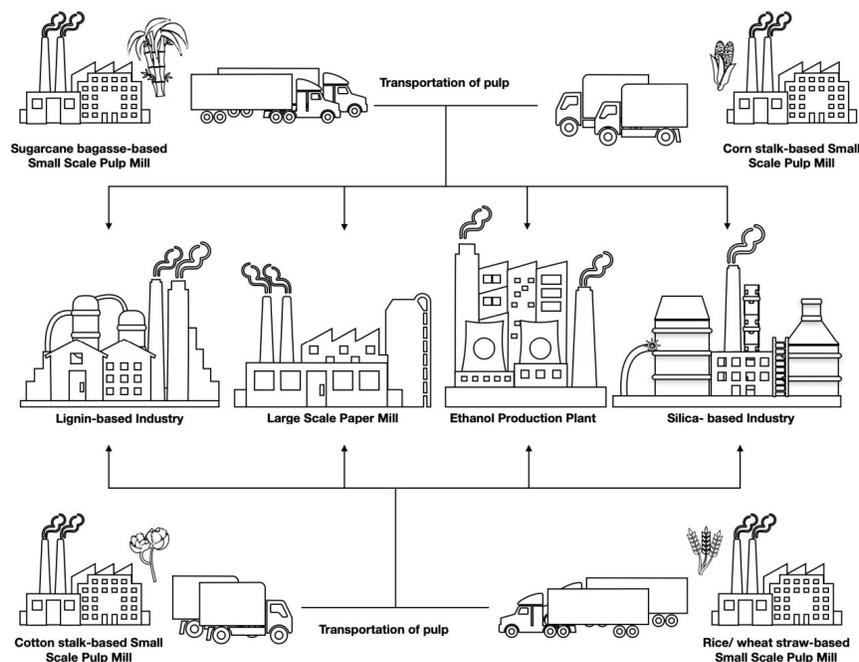
Lignocellulose is a recalcitrant composite, consisting of several tightly packed components, which are bonded to the phenolic polymer lignin, hampering the access to biomass components. Biorefinery processes consist in the fractionation of lignocellulosic components, through biochemical, thermochemical and hydrothermal routes, and their subsequent conversion to chemicals, energy and materials (Scheme 1).

Nowadays, biological and thermal processes are integrated with sustainable and cost-effective industrial applications.¹⁰⁷ Laser *et al.*, for example, conducted the pretreatment of sugarcane bagasse with liquid hot water (LHW) and steam.¹⁰⁸ The key performance metrics of these pretreatments included fibre reactivity, xylan recovery, and the extent to which the pretreatment hydrolyzate inhibited glucose fermentation. In four cases, the LHW pretreatment achieved $\geq 80\%$ conversion by simultaneous saccharification and fermentation (SSF), $\geq 80\%$ xylan recovery, and no hydrolyzate inhibition of glucose fermentation. Abdulkhani *et al.* treated raw bagasse directly with sodium sulfite in acidic and neutral conditions to produce bagasse lignosulfonate.¹⁰⁹ In addition, the sugar impurities in lignosulfonates were fermented to ethanol using *Candida guilliermondii*.

The hydrothermal treatment of bamboo dissolved 15% of biomass, which constituted 1% lignin and 6-7% sugars;¹¹⁰ the by-product

lignin was converted to adhesives and different chemicals through a chemical

reaction⁶⁵ (Scheme 1c).



Scheme 3: Schematic of non-wood community pulping, cellulose and bio-based materials industries

Even after the fractionation of lignocellulosic components, biological, physical, chemical and thermal processes are required to produce final products, such as biochemicals, biofuels, biomaterials and cellulosic products. The physical/chemical treatment of cellulose, followed by a biological treatment, provides maximum effectiveness of the biorefinery.¹¹¹⁻¹¹³ In the conversion of cellulose pulp into methyl cellulose, a physical treatment followed by a chemical reaction improved the degree of substitution.¹¹⁴ An efficient biorefinery can be achieved through combined treatments.

CONCLUDING REMARKS

The demand for pulp and paper related products in Bangladesh is increasing with the country's economic development. It is estimated that the demands for bio-based products will rise up to ten fold by 2030. Therefore, the government should initiate a masterplan for the pulp and paper industries to minimize the foreign currency expense for importing raw materials and paper products. Bangladesh generates huge amounts of agricultural residues, which are characterized by lower lignin and moderate cellulose

contents, and can be used as raw materials for the pulp and cellulose industry. Most of the non-woods contain high amounts of fines and ashes, which hinders conventional pulping processes. Organic acid and KOH pulping processes overcome the drawbacks of non-wood pulping with the integration of biorefinery. The pulping and papermaking properties of most agricultural residues are satisfactory. In addition, *T. orientalis* is a fast-growing wood species that possesses a vast potential for pulping in Bangladesh. The government can adopt a plantation scheme using this species under the social forestry program, which will also create employment opportunities. Finally, it can be concluded that non-wood plants and *T. orientalis* are promising alternatives for pulp production in Bangladesh.

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