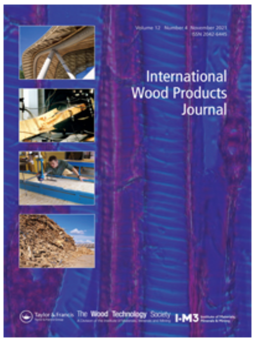

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RESEARCH ARTICLE

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Evaluation of *Erythrina fusca*Lour. as a pulping raw material

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ABSTRACT

This paper characterizes *Erythrina fusca* Lour. in terms of anatomical, morphological and chemical properties to evaluate its efficacy as a pulping raw material. It is characterized with 47.0% α-cellulose and 28.8% lignin content with a fibre length of 1.11 mm. The vessels (pores) are distinct and form porous semi-rings, with a row of larger pores at the beginning of the growth layer, which facilitate penetration of chemicals during the cooking phase of pulping. Kraft pulping of *E. fusca* was carried out by varying cooking temperature, time and alkali charge. At optimum condition of 14% active alkali for 2 h of cooking at 170°C, pulp yield was 40% with kappa number of 26.6. The papermaking properties were also evaluated and showed tensile index of 52.4 N m g^{-1} with tear index of6.8 mN m^2 g^{-1} at °SR of 57. This species can be used as a raw material for writing and printing grade pulp.

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Fast-growing tree; α-cellulose; fibre length; pulp yield; papermaking properties; kappa number; fibre wall thickness; parenchyma

Introduction

Worldwide many trees are cultivated, random deforestation is getting less and less. The contribution of wood is 90–95% of total pulp production (Laftah and Wan Abdul Rahman 2016). The pulp and paper industry is growing faster, resulting in a massive demand for pulping raw materials, which causes random deforestation ultimately consequences in global warming. Although non-wood and recycled wastepaper showed some promising potentiality as a source of raw materials, one of the best possible remedies is to use annual plants and fast-growing wood planted in allocated land as raw material in the pulp and paper industry. The forest resources in Bangladesh are relatively very limited, and under tremendous pressure due to different anthropogenic activities (DoE 2019). Therefore, it necessitates to find out alternative sources of raw materials to survive our pulp and paper industries in Bangladesh. Bangladesh has only 38,000 ha of allocated forest land for pulpwood (Anon 2021b). Fast-growing wood plantation can produce one and a half to two times more wood per hectare per year and reach maturity two to three times faster than longer-rotation softwood plantations (Cossalter and Pye-Smith 2003). Different fast-growing trees such as *Acacia auriculiformis, A. mangium*, *Trema orientalis*, *Gmelina arborea*, etc. have been explored to produce more wood using the same land, and pulpwood quality has also been evaluated (Jahan and Mun 2004, 2011; Haque et al. 2019; Sarkar et al. 2021; Sharma et al. 2021).

Among these species, *T. orientalis* is a native and underutilized fastest-growing species in Bangladesh and studied comprehensively. *Trema orientalis* could be mature for pulpwood within 3–4 years (Jahan and Mun 2003, 2004; Jahan et al. 2010). Recently, another fast-growing and underutilized species, *Erythrina fusca* Lour. (Family: Fabaceae) has been identified as a potential resource of pulpwood. It is highly adapted even to coastal conditions, tolerant of both flooding and salinity.

Erythrina fusca is a medium to large, much-branched, soft-wooded, deciduous tree, strongly recommended as a multipurpose tree for agro-forestry (http://www.worldagroforestry.org/). Generally, the tree grows 10–15 m tall, sometimes the specimens as tall as 26 m. As a member of the family Fabaceae, *E. fusca* fixes atmospheric nitrogen to the soil which improves the soil quality (Leblanc et al. 2007). It is widely grown, especially in tropical America, as a shade tree for coffee and cocoa (Anon 2021a). Many studies have been carried out on this tree for medicinal value (Khaomek et al. 2008; Innok et al. 2009, 2010). Hitherto, no information has been reported on pulpwood quality and pulping of this species.

Therefore, anatomical, morphological and chemical properties of *E. fusca* were assessed as pulpwood. Pulping of *E. fusca* was evaluated in kraft process by

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varying active alkali charge, cooking time and temperature. Papermaking properties of *E. fusca* pulps were also determined.

Materials and methods

Materials

Erythrina fusca tree was collected from the Savar area of Dhaka district (23° 51′ 30.0024″ N and 90° 16′ 0.0120″ E). Three trees were selected for this experiment at the age of 6 years. The average DBH of the trees was 28 cm. Tree was naturally grown, therefore, seed and silvicultural conditions were not known. Fifty centimeter from top and bottom and branches of these trees was discarded, and the remaining portion was debarked and chipped to $0.5 \times 0.5 \times 2$ cm size. The chips were ground in a Wiley mill and 40–60 mesh size was used for chemical analysis.

Morphological and chemical properties

For the measurements of fibre length, sample was macerated in a solution containing 1:1 HNO_3 and $KClO_3$. A drop of macerated sample was taken on a slide. The fibre diameter and length were measured in image analyzer Euromex-Oxion using Image Focus Alpha software. Average reading was taken from the 200 fibres measurement.

The extractive (T204 om88), 1% alkali solubility (T 212 om98), water solubility (T207 cm99), Klason lignin (T211 om83) and ash content (T211 os76) were determined in accordance with Tappi Test Methods. Holocellulose was determined by treating extractive free wood meal with $NaClO_2$ solution. The pH of the solution was maintained at 4 by adding CH_3-COOH-CH_3COONa buffer and α-cellulose was determined by treating holocellulose with 17.5% NaOH.

Anatomical properties

For anatomical analysis, wood blocks of 1 cm length was prepared from the wood at the DBH. Transverse micro sections from blocks of 30 μm thickness were obtained using a sliding microtome (Leica SM2010R). For light microscopy micro sections were stained with Safranin, dehydrated in alcohol and mounted in Canadian balsam on glass and investigated under an image analyzer (Model, Euromex, The Netherlands). SEM image of dehydrated cross-section was sputter coated and photograph was recorded using a scanning electron microscope (Model EV018, Carl Zeiss AG, Germany). For each sample, 100 measurements were done.

Pulping

Pulping was carried out in a thermostatically controlled electrical oil bath containing four vessels made of stainless steel having 1.5 litres of volume of each vessel. The capacity of the digester was 1.5 litres. The normal charge was 200 g of oven-dried (o.d.) *E. fusca*. Pulping conditions of kraft process are as follows:

- Active alkali charges were 12, 14, 16 and 18% on oven-dry (o.d) raw material as Na_2O.
- Cooking times were 1 and 2 h at maximum temperatures150, 160 and 170°C.
- Liquor to material ratio was 4.
- Sulphidity 30% for kraft process.

After digestion, the pulp was washed till free from residual chemicals and screened by flat vibratory screener (Yasuda, Japan). The screened pulp yield, total pulp yield and screened reject were determined gravimetrically as a percentage of o.d. raw material. The kappa number (T 236 om-99) of the resulting pulp was determined in accordance with Tappi Test Methods. Three replicates of all experiments were done and average reading was taken.

$D_0(EP)D_1$bleaching

Pulps were bleached by $D_0(EP)D_1$ bleaching sequences in plastic bag. D_0, D_1 and EP denoted chlorine dioxide in the first stage, chlorine dioxide in the 2nd stage and peroxide reinforced alkaline extraction, respectively. In the first stage (D_0) of D_0EpD_1 bleaching sequences ClO_2 charge was 1.5%. The initial pH was adjusted to 2.5 by adding dilute H_2SO_4. In the alkaline extraction stage, NaOH and H_2O_2 charges were 2% and 0.5% (on od pulp), respectively. The temperature was 70°C for 60 min and pulp consistency was 10%. In the D_1 stage, the end pH was 4. The ClO_2 charge in the D_1 was 1.0%.

Evaluation of Kraft pulp

Kraft unbleached pulps were beaten in a PFI mill at different revolutions to different freeness (°SR) and hand sheets of about 60 g m^{-2} were made in a Rapid Kothen Sheet Making Machine. The sheets were tested for tensile (T 494 om-96), burst (T 403 om-97) and tear strength (T 414 om-98) according to TAPPI Standard Test Methods. The fibre quality of the pulp samples was by Fibre Quality Analyzer – 360, OpTest, Canada.

Statistical analysis

Descriptive statistics such as mean and standard deviation of anatomical, morphological, chemical and physical properties of *E. fusca* and its derived value were performed. Correlation among cooking properties, Physical properties and fibre quality parameters

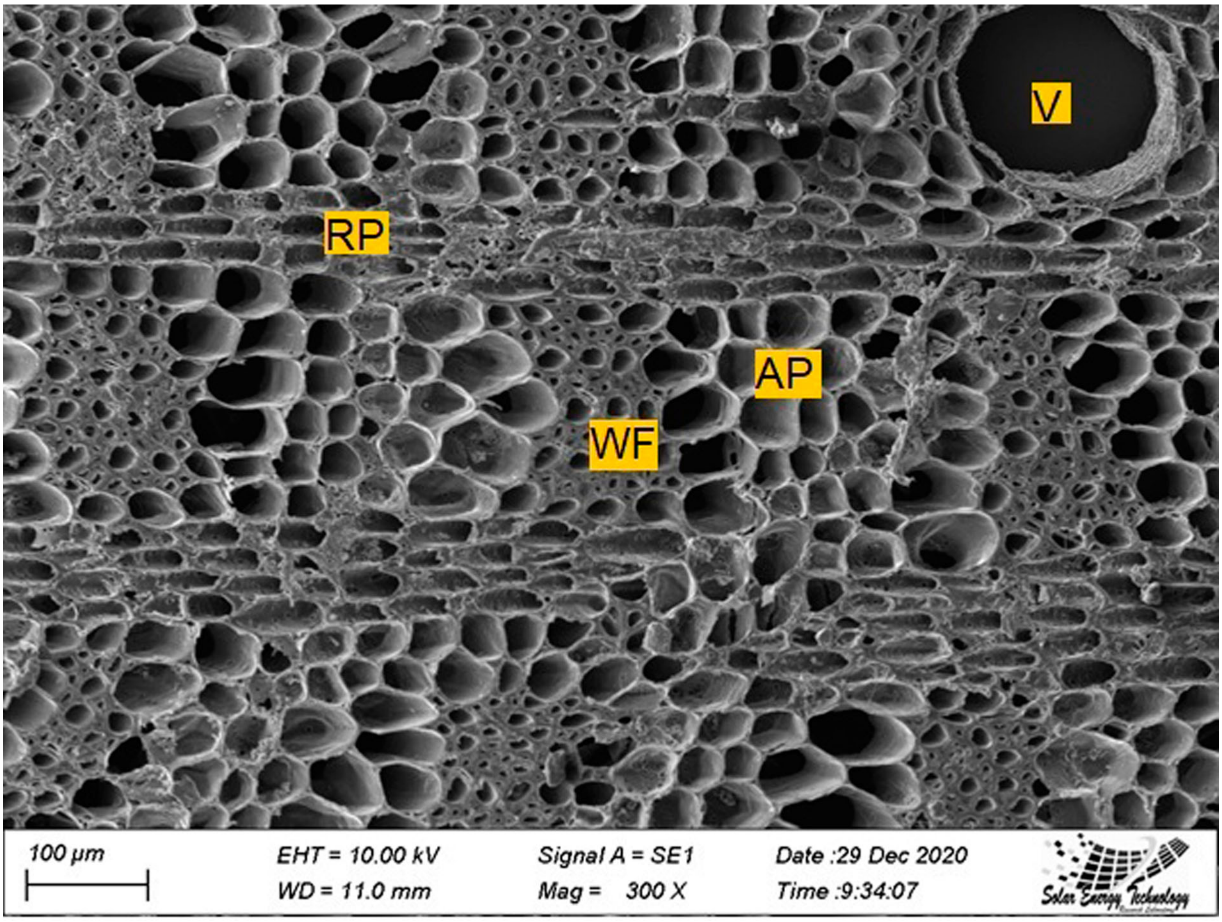

Figure 1. Cross-section of *Erythrina fusca* stem under Scanning Electron Microscopy. V Xylem vessel; WF Wood fibre; RP Ray parenchyma; AP Axial parenchyma.

of Kraft pulping of *E. fusca* to show their association. Significance of each correlation was tested with Student's *t*-test. Multivariate regression analysis was performed to explore the changes of pulp yield and kappa number on pulping parameter such as active alkali (%), temperature (°C) and time (h). Efficiencies of regression models were expressed in terms of coefficient of determination (R^2). Correlation and multivariate regression analysis have been done with 21 samples ($n = 21$). Computer software, SPSS of its version 22.0 was used for data analysis.

Results and discussion

Anatomical characteristics

The vessels (pores) are distinct and form semi-ring porous, with a row of larger pores at the beginning of the growth layer. These pores are sparsely distributed and small-sized toward the end of the layer. The vessels (pores) are circular as seen in cross-section, thin-walled structures, in dendritic pattern (Figure 1). Pores are mostly solitary or in radial rows of two to some pores or in clusters. The pores are wide and narrow within any annual ring. The axial parenchyma is predominant, confluent and in wide tangential bands. The growth layers are distinct, and the beginning is marked by the distribution of the semi-porous rings and the presence of thick-walled xylem. The longitudinal cells within an annual ring are fibres and are usually thick-walled. Rays are very wide, homogenous type and storied. Usually, 3–4 seriate, having many cells across their width.

Table 1 shows the anatomical properties of *E. fusca*. The vessel proportion of *E. fusca* was very similar to *Acacia auriculiformis* (14%) but of vessel per sq mm was lower than *A. auriculiformis* due to wider vessel in *E. fusca* (Table 1). More than 9% vessel proportion was found in *A. mangiun* (Sahri et al. 1993). The higher percentage of vessel facilitates the penetration of pulping liquor into the wood, but the surface quality of the paper becomes lower due to vessel pick out from the paper surface during the printing process (Colley

Table 1. Quantitative anatomical properties of *E. fusca*.

	E. fusca	*Acacia auriculiformis* (Jahan et al. 2019)
Vessels (%)	14.17 ± 1.42	14.08
No. of Vessel/mm^2	2.0 ± 0.47	11.04
Rays (%)	21.55 ± 3.67	6.7
Axial Parenchyma	39.92 ± 12.59	–
Fibre (%)	24.36 ± 4.45	73.34

Table 2. Morphological properties of *E. fusca* and its derived value.

	E. fusca	*Acacia auriculiformis* (Jahan et al. 2019)
Fibre length (mm)	1.11 ± 0.18	0.911
Fibre diameter (μm)	22.93 ± 4.20	18.27
Lumen diameter (μm)	9.80 ± 4.4	15.71
Wall thickness (μm)	2.94 ± 0.66	2.46
Slenderness ratio	48.45 ± 7.41	49.86
Flexibility coefficient	42.74 ± 12.69	85.9
Runkel ratio	0.6 ± 0.35	0.31

1973; Amidon 1981) and produces a lower pulp yield (Haygreen and Bowyer 1996). Amidon (1981) showed that the vessel proportion and the number of vessels per sq mm were negatively correlated with pulp yield and paper strength properties. Axial parenchyma and ray cells proportion were 39.92% and 21.55%, respectively (Table 1). It is clearly seen in the cross-section of SEM and optical microscopy picture (Figure 1). The axial parenchyma is predominantly paratracheal and more abundant. Similarly, this was observed in Brazilian species (Alves and Angyalossy-Alfonso 2002). Ona et al. (2001) showed that the ray proportion negatively correlated with pulp yield, burst factor, breaking length, kappa number and unbleached brightness.

Fibres proportion of *E. fusca* was very low only 24.36%, due to the high percentage of parenchyma cells, while the proportion of the fibre in *A. auriculiformis* was 73.34% (Table 2), which included the axial parenchyrma cells.

Morphological properties

Morphological characteristics of fibres including fibre length, fibre width, fibre wall thickness, and lumen diameter are important parameters for evaluating the papermaking properties (Wangaard and Williams 1970; Seth 1990; Ferdous et al. 2021). Table 2 shows the morphological properties and its derived values, which are important in assessing the suitability of fibrous raw material for pulping. The fibre length of *E. fusca* was 1.11 mm and longer than *Casuarina equisetifolia* (Sarkar et al. 2021) and *Acacia auriculiformis* (Table 2) and close to typical hardwood (Ferreira et al. 2011). A higher tearing strength of paper is obtained from a longer fibre pulp (Gallay 1962). Ferdous et al. (2021) showed that the tear index of both refined and unrefined pulps was directly correlated with fibre length of pulp.

Fibre width of *E. fusca* was 22.93 μm, which was higher than *A. auriculiformis*. In the paper web, fibre width affects the fibres cross over. If the fibres are wide, then the area per crossover increases where the fibres are held together which contribute to the strength of paper. For a given fibre length, the fibres with higher fibre width give higher paper strength due to increased crossover area per fibre. The length to width ratio of fibre is called slenderness. But the shorter and wider fibre produces a poor slenderness ratio, which in turn reduces tearing resistance. The slender ratio of *E. fusca* fibre was 48.45 while it was 49.86 for *A. auriculiformis* (Table 2). Fibre width and wall thickness affected fibre flexibility. Fibre flexibility coefficient was only 42.74. Thick-walled fibres adversely affected the bursting strength, tensile strength and folding endurance of paper. The fibrewall thickness of *E. fusca* was 2.94 μm, which was thinner than other hardwoods (Jahan et al. 2019).

The Runkel's ratio is an important derived value of fibre determining the strength properties of the paper. The fibres with Runkel ratio less than 1 is easily collapsible, consequently producing paper sheet with enhanced bonding of fibres, thereby considered ideal for paper making. The Runkel ratio of *E. fusca* was 0.6, which was higher than *A. auriculiformis* (Jahan et al. 2019). Considering all morphological properties, it can be said that *E. fusca* fibre would produce paper with moderate papermaking properties.

Chemical characteristics

The α-cellulose content in wood is a determining factor of pulp yield. As shown in Table 3, the α-cellulose content in *E. fusca* was 47.0%, which was higher than *A. auriculiformis* (Haque et al. 2019b) and *T. orientalis* (Jahan and Mun 2004; Jahan et al. 2010) grown in Bangladesh, thus suitable for pulping.

Lignin is an undesirable part of pulping. The lignin content in *E. fusca* was higher than other common hardwoods for pulping (Patt et al. 2006) and *T. orientalis* (Jahan et al. 2010) and close to *Acacia* hybrid (Haque et al. 2019b), those are potential pulpwood in Bangladesh. Pentosan is the main constituent of hardwood hemicellulose. Pentosan content was extremely low (8.24%), which was reflected by holocellulose content (59.2%). The pentosan content was even lower than other common hardwoods (Timell 1967; Patt et al. 2006) and native hardwood in Bangladesh (Jahan and Mun 2004; Haque et al. 2019b, 2019a) and mangrove species (Mun et al. 2011). Hemicellulose facilitates fibre bonding during sheet formation.

Table 3. Chemical and physical properties of *E. fusca*. Note: Table 2 and 3 need to be exchanged)

	E. fusca	*Trema orientalis* (Jahan et al. 2010)
Extractive (%)	1.09 ± 1.07	0.81-89
Cold water solubility (%)	4.9 ± 0.61	–
Hot water solubility (%)	7.8 ± 1.49	–
1% alkali solubility (%)	12.4 ± 4.72	–
Holocellulose (%)	59.2 ± 11.61	74.4–78.5
α-cellulose (%)	47.0 ± 7.55	42.5–45.1
Pentosan (%)	8.24 ± 2.11	21.2–23.5
Klason lignin (%)	28.8 ± 9.21	23.6–24.1
Acid soluble lignin	–	2.2–2.9
Ash Content (%)	3.33 ± 0.88	1.1–1.2
Density (g/cc)		0.357–0.380

Table 4. Kraft pulping of *E. fusca*.

Active alkali charge (%)	Temperature, °C	Time, h	Pulp yield (%) Screened	Reject	Total	Kappa number
12	170	1	36.07	9.50	45.51	39.35
14	170	1	39.78	2.65	42.44	34.89
16	170	1	41.05	0.95	41.98	28.80
12	170	2	40.07	1.34	41.41	34.92
14	170	2	39.80	0.35	40.15	26.56
16	170	2	35.77	0	35.77	19.70
14	150	2	30.62	18.1	48.72	39.28
14	160	2	39.64	2.00	41.64	34.58

One percentage of caustic soda solubility of *E. fusca* was 12.4%, which was close to *A. oriculiformis* (Haque et al. 2019b). This is attributed to the presence of lower inorganics, tannins, gums, sugars and of lower molecular carbohydrates and other alkali-soluble materials. Acetone extract of *E. fusca* was 1.09%. The ash content in *E. fusca* was higher (3.3%) than hardwoods that is detrimental in pulp processing.

Pulp yield and kappa number

Erythrina fusca was cooked in kraft process with varying active alkali charge, time and temperature and results are shown in Table 4. As expected, screened reject, pulp yield and kappa number decreased with increasing active alkali charge, time and temperature. The screened pulp yield increased from 36.07% to 41.05% and reject decreased from 9.5% to 0.95% with increasing active alkali charge from 12% to 16% at 170°C for 1 h, where kappa number decreased from 39.35 to 28.80. With the increase of cooking time to 2 h at 170°C for 14% active alkali, reject decreased to 0.35 with almost similar screened pulp yield and 8.33 points lower kappa number. At the 14% active alkali charge for 2 h of cooking at 150°C the screened pulp yield was 30.62% only with very high screened reject (18.1%) and kappa number (39.28), which increased to 39.64% with the stringent decrease of screened reject (2%) in increasing of cooking temperature to 160°C, but kappa number did not decrease to desire level (34.58). Therefore, optimum conditions for *E. fusca* were considered at 170°C for 2 h of cooking in 14% active alkali charge. The pulp yield of *E. fusca* was lower than *Acacia* hybrids, where 18% active alkali charge was required in 120 min of cooking at 170°C reaching kappa number 27.6 with pulp yield of 45.9% and no reject. *Erythrina fusca* was easier to cook due to porous anatomical structure (Figure 1).

As shown in Table 5, there is a strong and significant association between pulp yield (%) and kappa number ($r = 0.89$). On the contrary, Kappa number is strong but negatively correlated with active alkali chare (%) ($r = -0.72$). Moderate but negative association between Pulp yield (%) and temperature ($r = -0.63$) has been noticed in the analysis.

The regression model for predicting pulp yield (PY) on the basis of Active Alkali (AA), temperature (temp) and time is significant ($p = 0.011$) with predictive efficiency, coefficient of determination $R^2 = 0.92$ and adjusted $R^2 = 0.86$.

PY = 140.96-1.15*AA-0.45*temp-4.49*time ($R^2 = 0.92$, Adjusted $R^2 = 0.86$).

PY- Pulp yield, AA-Active alkali, KN- Kappa number.

The regression model for determination of Kappa number (KN) based on Active Alkali (AA), temperature (temp) and time is significant ($p = 0.001$) with predictive efficiency, coefficient of determination $R^2 = 0.98$ and adjusted $R^2 = 0.96$.

KN = 140.96-1.15*AA-0.45*temp-4.49*time ($R^2 = 0.92$, Adjusted $R^2 = 0.86$).

Changes in active alkali (%), temperature (°C) and time (h) have significant negative impact both on pulp yield and kappa number.

Papermaking and pulp fibre properties

Physical strength properties of unbleached *E. fusca* pulps at different drainage resistance (°SR) are given in Table 6. In the unrefined state of pulp, the °SR was 17, where tensile, tear and burst indexes were 22.72 N m g^{-1}, 8.09 mN m^2 g^{-1} and 1.36 kPa m^2 g^{-1}, respectively. The tensile and burst index increased

Table 5. Correlation among cooking properties of Kraft pulping of *E. fusca*.

	Active alkali charge (%)	Temperature (°C)	Time (h)	Pulp yield (%)	Kappa number
Active alkali charge (%)	1	0.00	0.00	−0.458	−0.719*
Temperature (°C)	0.00	1	−0.417	−0.633	−0.464
Time (h)	0.00	−0.417	1	−0.243	−0.255
Pulp yield (%)	−0.458	−0.633	−0.243	1	0.891**
Kappa number	−0.719*	−0.464	−0.255	0.891**	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table 6. Physical properties of *E. fusca* pulp.

°SR	Tensile index, Nm g^{-1}	Tear index, mN.m^2 g^{-1}	Burst index, kPa.m^2 g^{-1}	Elongation, mm	TEA, J m^{-2}
17	22.72 ± 1.6	8.09	1.36	1.91 ± 0.43	18.57 ± 5.63
35	46.23 ± 2.88	8.72	3.21	3.41 ± 0.37	69.46 ± 11.90
57	52.38 ± 3.6	6.76	3.46	3.49 ± 0.43	81.03 ± 15.89
70	49.63 ± 5.07	6.23	3.31	3.72 ± 0.50	82.83 ± 18.58

Table 7. Fibre quality of *E. fusca* pulp on valley beating.

°SR	Fines (%)	Mean Length (mm)	Mean Curl Index	Mean Kink Index (mm^{-1})	Mean Width (μm)	Degree of External Fibrillation (%)	Coarseness (mg m^{-1})
17	56.1	0.501	0.111	1.85	17.3	1.38	0.157
35	56.8	0.402	0.084	1.59	16.9	1.89	0.123
57	58.6	0.325	0.084	1.73	17.1	2.4	0.093
70	57.7	0.293	0.097	1.86	18.5	4.37	0.089

Table 8. Association between physical properties of *E. fusca* pulp.

	°SR	Tensile index (Nm g^{-1})	Tear index (mN m^2 g^{-1})	Burst index (kPa m^2 g^{-1})	Elongation (mm)	TEA (J m^{-2})
°SR	1	0.851	−0.855	0.818	0.868	0.890
Tensile index (Nm g^{-1})	0.851	1	−0.499	0.996**	0.979*	0.994**
Tear index (mN m^2 g^{-1})	−0.855	−0.499	1	−0.432	−0.488	−0.545
Burst index (kPa m^2 g^{-1})	0.818	0.996**	−0.432	1	0.984*	0.990*
Elongation (mm)	0.868	0.979*	−0.488	0.984*	1	0.993**
TEA (J m^{-2})	0.890	0.994**	−0.545	0.990*	0.993**	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

and tear index decreased with increasing drainage resistance (°SR) from 17 to 57, further increase of ° SR decreased all these strength properties. A continuous decrease of tear index with °SR can be explained by shortening fibre length as observed by fibre quality parameters (Table 7). Total Energy absorption and Elongation were increased with pulp refining.

Correlation of papermaking properties with °SR is given in Table 8. °SR is strongly and positively correlated with tensile index, burst index, elongation, TEA ($r = 82$–90), but negatively associated with tear index ($r = 86$). Tensile index is very strongly and positively correlated with burst index, elongation and TEA ($r \approx 0.99$). Significant strong positive association has been noticed between burst index and tensile index, elongation and TEA ($r \approx 0.99$). Elongation (mm) is very strongly and positively associated with tensile index and TEA ($r = 0.99$), elongation ($r = 0.98$) and °SR ($r = 0.87$). TEA is very strongly and positively associated with can be noticed between tensile index, burst index and elongation ($r = 0.99$) and strongly with °SR ($r = 0.89$).

The beating process changes the structure and properties of fibres, such as fibre swelling, fibre shortening, internal and external fibrillation, etc. As the pulp is increasingly refined in Valley beater, the degree of external fibrillation increases with the formation of fines (Table 7). Kang and Paulapuro (2006) showed that the formation of the fine increased continuously along with the increase in external fibrillation. Table 6 also shows that fibre length and fibre coarseness decreased continuously on the Valley beating of

Table 9. Correlation among the fibre quality parameters.

	°SR	Fines (%)	Mean Length (mm)	Mean Curl Index	Mean Kink Index (mm^{-1})	Mean Width (μm)	Degree of External Fibrillation (%)	Coarseness (mg m^{-1})
°SR	1	0.839	−0.988*	−0.464	0.148	0.627	0.901	−0.976*
Fines (%)	0.839	1	−0.870	−0.648	−0.053	0.179	0.532	−0.908
Mean Length (mm)	−0.988*	−0.870	1	0.594	0.003	−0.513	−0.843	0.996**
Mean Curl Index	−0.464	−0.648	0.594	1	0.784	0.346	−0.125	0.636
Mean Kink Index (mm^{-1})	0.148	−0.053	0.003	0.784	1	0.718	0.389	0.041
Mean Width (μm)	0.627	0.179	−0.513	0.346	0.718	1	0.887	−0.445
Degree of External Fibrillation (%)	0.901	0.532	−0.843	−0.125	0.389	0.887	1	−0.794
Coarseness (mg m^{-1})	−0.976*	−0.908	0.996**	0.636	0.041	−0.445	−0.794	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table 10. Bleaching of *E. fusca* pulp.

Satge	Kappa number	Viscosity (mPa.s)	Brightness (% ISO)	Yield (%)
Unbleached	26.56	22.0	21.2	100
D_0	–	–	–	–
E_p	5.3	20.7	60.2	–
D_1	1.2	18.8	81.6	90.6

pulp. Fibre length is very important for tear strength when the level of fibre bonding is moderate (Wangaard and Williams 1970; Ferdous et al. 2021), which was reflected in the tear index of *E. fusca* pulp (Table 6). Wimmer et al. (2002) also showed that the fibre length had a strong, direct effect on tear index.

As expected, fibres are straightened on beating, curl index decreased from 0.111 to 0.084 with increasing °SR from 17 to 57, consequently increasing the mechanical properties of paper (Page 1985b, 1985a). Gao et al. (2015) also showed that increasing beating intensity decreased coarseness proportionally. The fibre deformations (Curl and kink) decreased fibre segment activation in the fibrenetwork. Joutsimo et al. (2005) demonstrated that the decreased fibre segment activation resulted in decreased tensile and stiffness indices. The fibre coarseness influence virtually all pulp properties - drainage, wet-web strength, and the structural, strength, and optical properties of the dry sheets (Seth 1990).

Multiple comparison analyses of fibre quality parameters are illustrated in Table 9. ^{0}SR is strongly and positively associated with Fines ($r = 0.84$), Degree of external Fibrillation ($r = 0.90$), but negatively correlated with Mean length ($r = -0.99$) and Coarseness ($r = -0.98$). Fines are strongly and negatively correlated with Mean length ($r = -0.87$) and Coarseness ($r = -0.91$). Mean length is very strongly and positively correlated with Coarseness ($r = 0.99$), but strongly negatively associated with ^{0}SR ($r = -0.99$), Fines ($r = -0.87$), Degree of external Fibrillation ($r = -0.84$).

Bleaching of E fusca

In order to evaluate the bleaching potential of *E. fusca* pulp obtained at the optimum conditions was bleached in conventional $D_0(EP)D_1$ bleaching sequences. The kappa number, viscosity and brightness of unbleached pulp was 26.56, 22.0 mPa.s and 21.2%, respectively (Table 10). In the first delignification stage (D_0), residual lignin dropped rapidly, consequently kappa number decreased to 5.3 and brightness increased to 60.2% with minor viscosity dropped. In the final stage of bleaching (D_1), pulp brightness increased to 81.6% with the ClO_2 consumption of 25 kg/MT pulp, where viscosity reduced to 18.8 mPa.s. The bleachability of *E. fusca* pulp was better than different acacia species (Haque et al. 2019).

Conclusion

E. fusca wood consists of vessel, parenchyma and fibre, the axial parenchyma is predominant, confluent and in wide tangential bands. The fibre length (1.11 mm) is close to tropical hardwoods. The α-cellulose content was 47.0%, which shows suitability for pulping, but the lignin content was higher, implies disadvantageous for pulping. *E. fusca* requires comparatively mild cooking conditions as the raw material is porous. At optimum condition of 14% active alkali for 2 h of cooking at 170°C, pulp yield was 40% with kappa number of 26.6. The papermaking properties of *E. fusca* pulp are comparable to other tropical hardwoods. Considering, all these properties, this can be a good substitute of hardwood in Bangladesh.

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