Chemithermomechanical Pulping and Properties Comparison of Four Common Hardwood Species in Northern China

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Populus cathayana Rehder (PCR, Chinese poplar), *Fraxinus chinensis* Roxb. (FCR, Chinese ash), *Platanus orientalis* L. (PO, Oriental plane), and *Acer palmatum* Thunb. (AP, Japanese maple) are four common hardwoods in the northern hemisphere. In this work, chemithermomechanical pulps (CTMP) of the four wood species were prepared for comparative study of pulp properties. For unbleached CTMP, PCR and FCR exhibited the highest whiteness of 44%ISO, while AP demonstrated the highest tensile index of 24.2 N·m²/g, tear index of 1.23 mN·m2/g, and ring crush index of 7.2 N·m/g. For bleached CTMP using hydrogen peroxide, PO achieved the highest whiteness of 70.3% ISO at 6% hydrogen peroxide. AP showed the optimal tensile index of 24.7 N·m²/g. The experiments also revealed that PO exhibited the highest bulk of 3.6 cm³/g. This study provides a reference for selecting raw materials in pulp production.

DOI: 10.15376/biores.20.2.3604-3611

Keywords: Hardwood; Chemithermomechanical; Paper properties; Pulp

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INTRODUCTION

The raw materials commonly used in the paper industry include plant fibers and non-plant fibers. Plant-fibers are primarily from softwood, hardwood, and herbaceous plants (Reis *et al.* 2018; Liang *et al.* 2022; Gao *et al.* 2023; Jančíková *et al.* 2024). *Populus cathayana* Rehder (PCR, density: 0.35 to 0.50 g/cm³), *Fraxinus chinensis* Roxb. (FCR, density: 0.45 to 0.65 g/cm³), *Platanus orientalis* L. (PO, density: 0.55 to 0.65 g/cm³), and *Acer palmatum* Thunb. (AP, density: 0.60 to 0.75 g/cm³) are four common hardwoods in the northern part of China. PCR, which has strong adaptability, fast growth, and stable properties, is frequently used as a short-cycle industrial raw material. FCR, known for its hardness, wear resistance, and durability, is commonly used in furniture and construction and is also an ornamental tree. PO grows rapidly, has relatively low density and soft wood, and is a common greening tree species in northern China. AP, with its leaves and tree shape, is a widely used ornamental species in landscaping. The four hardwoods are also important raw materials for papermaking due to their short growth cycles and fast regeneration.

Pulping methods can be categorized into chemical pulping, semichemical pulping, chemimechanical pulping, and mechanical pulping based on the increasing mechanical energy required to separate fibers and the decreasing reliance on chemical treatments (Rudi *et al.* 2016; Bajpai 2018; Lin *et al.* 2020; Alvarado-Morales *et al.* 2021). Among these pulping methods, chemimechanical pulping is favored for the reduced environmental impact compared to chemical pulping and the improved pulp strength and durability compared to mechanical pulp (Lei *et al.* 2012). Chemithermomechanical pulping (CTMP) is a chemimechanical process that involves the use of chemicals and mechanical actions to separate wood fibers and produce pulp. In the course of CTMP pulping, wood chips are typically impregnated with sodium sulfite (Na_2SO_3) and sodium hydroxide (NaOH) at charges of 1 to 4% based on oven-dry wood. The pre-treatment is conducted at 60 to 90 °C for 30 to 60 minutes to soften lignin and improve fiber separation. Mechanical refining follows under atmospheric pressure to achieve desired fiber properties (Biermann 1996). CTMP produces a pulp that is lighter in weight compared to other methods, and therefore suitable for high bulk paper (Berg *et al.* 2021). High bulk paper plays a crucial role in book printing and publishing, especially for low-page-count books such as fiction novels and children's books. CTMP is ideal for tissue paper due to its high absorbency and softness.

In this work, CTMP was prepared from four common wood species in northern China, namely PCR, FCR, PO, and AP. Pulp handsheets were made for properties test. Comparisons of properties can aid in selecting wood for pulp production.

EXPERIMENTAL

Materials

PCR, PO, FCR, and AP were provided by a papermaking factory in Shandong. Ethylenediaminetetraacetic acid (analytical grade), sodium silicate (analytical grade), Magnesium sulfate (analytical grade), and hydrogen peroxide (3%) were purchased from Shanghai McLean Biotech Co., Ltd.

Table 1. Biomass Composition of the Four Woods

CTMP Pulps	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
Platanus orientalis L.	55%	15%	22%	0.7%
Populus cathayana Rehder	45%	25%	23%	1%
Fraxinus chinensis Roxb	50%	20%	25%	0.9%
Acer palmatum Thunb.	44%	25%	28%	1%

CTMP Pulping

Wood chips were washed using water. A spiral extrusion crusher was used to shred the chips into fibrous materials. The shredded material was steamed in a sterilizer at 102 °C for 10 min to expel air bubbles in the wood. Preimpregnation was conducted at atmospheric pressure and 100 °C in 4% NaOH for 30 min. A continuous high-consistency disc refiner was used for pulping at gap settings of 2.0, 1.0, 0.5, and 0.2 mm (non-consecutively). The refined pulp was sealed for storage.

Bleaching

Pulp (50 g), 1.5% (w/w) sodium silicate, 0.1% (w/w) magnesium sulfate, 2% (w/w) sodium hydroxide, and 0.1% (w/w) EDTA were placed in a self-sealing plastic bag. Three hydrogen peroxide levels of 2%, 4%, and 6% (w/w) were used for bleaching. Bleaching lasted for 120 min in a 90 °C water bath.

Handsheet Making

Pulp (2 g) and water were combined to a total volume of 1000 mL. The pulp slurry was dispersed thoroughly to test the beating degree. Pulp handsheets were prepared at a grammage of 80 g/m^2.

Testing

The pulp was subjected to fiber quality analysis (Valmet FS5). The paper samples were placed in a constant temperature and humidity chamber at 23 °C and 50% humidity for 24 h, followed by measurements of whiteness, bulk, tear strength, tensile strength, and ring crush strength. Three measurements were taken, and the average value was recorded. Whiteness was measured using a paper whiteness meter (L&W Elrepho 070, Zurich, Swiss Confederation), and tear strength was tested by cutting the paper samples into 6.3 cm long and 5 cm wide pieces, then using a tear tester (L&W Tearing Tester, Code 289, Zurich, Swiss Confederation). Tensile strength was tested by cutting the samples into 1.5 cm wide pieces and using a horizontal tensile strength tester (L&W Tensile Tester 066, Zurich, Swiss Confederation). Ring crush strength was measured by cutting the paper into pieces 1.52 cm long and 1.27 cm wide, then using a ring crush tester (Crush Tester 17-56, Veenendaal, Netherlands).

RESULTS AND DISCUSSION

Fiber length and width are crucial factors influencing the strength, surface smoothness, and other properties of paper (Chandra *et al.* 2019). Longer fibers enhance tensile and tear strength, while narrower and shorter fibers improve smoothness and flexibility. After refining treatments of pulp with disc gap settings of 2.0, 1.0, 0.5, and 0.2 mm of the disc refiner, the fiber quality analysis results for the four wood types are presented in Table 1. PCR exhibited the highest fiber width of 25.9 μm, while FCR displayed the lowest fiber width of 21.2 μm. PO demonstrated the longest average fiber length of 0.910 mm. PCR recorded the highest curl of 8.53% and the highest kink index of 1720 1/m, indicating a more deformed fiber structure. PO exhibited the lowest kink of 987 1/m and the highest fibrillation of 2.17%, suggesting better fiber bonding potential.

Table 2. Average Fiber Width and Length of CTMP Pulps from Four Woods

CTMP Pulps	Fiber Width (μm)	Fiber Length (mm)	Curl (%)	Kink (1/m)	Fibrillation (%)
Platanus orientalis	23.57	0.910	6.82	987.4	2,17
Populus cathayana	25.87	0.680	8.53	1720.8	2.00
Fraxinus chinensis	21.19	0.650	6.94	1443.3	1.72
Acer palmatum	21.71	0.543	6.56	1043.0	2.15

Freeness, which refers to the ability of water to drain through a fiber mat, is influenced by factors such as surface area, coarseness, fibrillation, flexibility, and fines content, and is widely used to monitor drainage rate changes during pulp beating and refining. High freeness typically reflects efficient fiber dispersion and rapid water removal, leading to stiffer paper with greater rigidity and lower flexibility, whereas lower freeness is associated with enhanced flexibility and elasticity, making the paper more suitable for applications that require softness and bending performance (Umair *et al.* 2020) or higher levels of inter0fiber bonding. Importantly, the relationship between refining and stiffness is non-linear: while initial refining improves fiber bonding and structural integrity—resulting in increased stiffness—excessive refining can lead to fiber shortening and over-fibrillation, which compromise the structural network and ultimately reduce stiffness despite improved flexibility. Achieving an optimal balance in refining is therefore crucial for tailoring the mechanical properties of the final paper product. The freeness of the four wood types, as shown in Table 2. The freeness of four CTMP pulp are relatively high, ranging from 625 to 680 mL, indicating the good water drainage behaviors.

The bulk of paper refers to its volume per unit weight. It is an important indicator of paper density and porosity. Bulkiness varies based on factors such as wood species, paper machine characteristics, and additives used in papermaking. High bulk paper plays a crucial role in book printing and publishing, especially for low-page-count books such as fiction novels and children's books. From Table 2, PO showed the highest bulk at 3.6 cm^3/g, while AP had the lowest at 2.47 cm^3/g. The whiteness of unbleached CTMP pulp from four wood showed little difference, ranging from 41.1% ISO to 44.1%ISO.

Table 3. Freeness, Bulk, and Whiteness of Unbleached CTMP Pulps from Four Wood Species

CTMP pulps	Freeness (mL)	Bulk (cm^3/g)	Yield (%)
Platanus orientalis	625	3.6	86.7
Populus cathayana	650	2.85	84.6
Fraxinus chinensis	680	3.23	85.6
Acer palmatum	680	2.47	84.0

The tensile strength, tear strength, and ring crush strength of pulp handsheets are crucial indicators of physical performance in various applications (Vieira and Rocha 2007; Larsson *et al.* 2018). Tensile strength determines the paper's ability to resist stretching, making it suitable for packaging materials and industrial papers. Tear strength reflects the paper's toughness and resistance to tearing, making it ideal for products like sack bag and bag paper. The ring crush strength correlates with edgewise compression strength of paperboard, and it is an important measure of the performance characteristics of corrugated board. The physical properties of pulp handsheets from unbleached CTMP pulps from the four woods are shown in Table 3. AP exhibited the highest tensile index of 23.9 $mN \cdot m^2/g$ and ring crush index of 7.46 $N \cdot m/g$, surpassing the other wood species in overall physical performance. Despite the short fiber length of AP, its exceptional strength can be attributed to its favorable fiber morphology (narrow width, low curl), chemical composition (moderate cellulose content, high hemicellulose content), and high density. These factors promote strong inter-fiber bonding and a compact fiber network, compensating for the disadvantage of shorter fiber length.

Table 4. Physical Properties of Pulp Handsheets Made of the Unbleached Pulps from Four Wood Species

CTMP pulps	Basis Weight (g/m^2)	Tensile Index (N·m/g)	Tear Index ($mN·m^2/g$)	Ring Crush Index (N·m/g)
Platanus orientalis	80.46	21.7±0.4	1.32±0.02	6.59±0.1
Populus cathayana	87.8	17.8±0.3	1.09±0.02	7.2±0.1
Fraxinus chinensis	77.47	17.43±0.3	0.95±0.02	6.23±0.1
Acer palmatum	89.09	23.87±0.4	1.23±0.02	7.46±0.1

Bleaching can improve the whiteness of pulp, making it more suitable for writing and printing. The CTMP pulps from four hardwood species were bleached using hydrogen peroxide at various dosages under alkaline conditions.

Figure 1 presents the whiteness, tensile index, tear index, and ring crush index under different hydrogen peroxide dosages. Before bleaching, the whiteness of PO pulp was lower than that of the other three wood pulps. However, when the hydrogen peroxide dosage reached 6%, the whiteness of PO pulp exceeded that of the other three wood pulps, reaching 72.07% ISO. AP exhibited superior tensile performance compared to the other three wood types, which can be attributed to its inherent density and fiber structure, leading to better tensile properties. At 2% hydrogen peroxide, the low-concentration bleaching of PO resulted in uneven penetration into the wood, leading to a decrease in strength to 18.7 N·m/g. Similarly, FCR experienced excessive reactions at 6% hydrogen peroxide bleaching, causing fiber damage and a decrease in strength to 12.95 N·m/g. For the tear and ring crush indices, the retention of lignin at 2% and 4% hydrogen peroxide helped maintain the integrity of the fiber network, thereby enhancing strength.

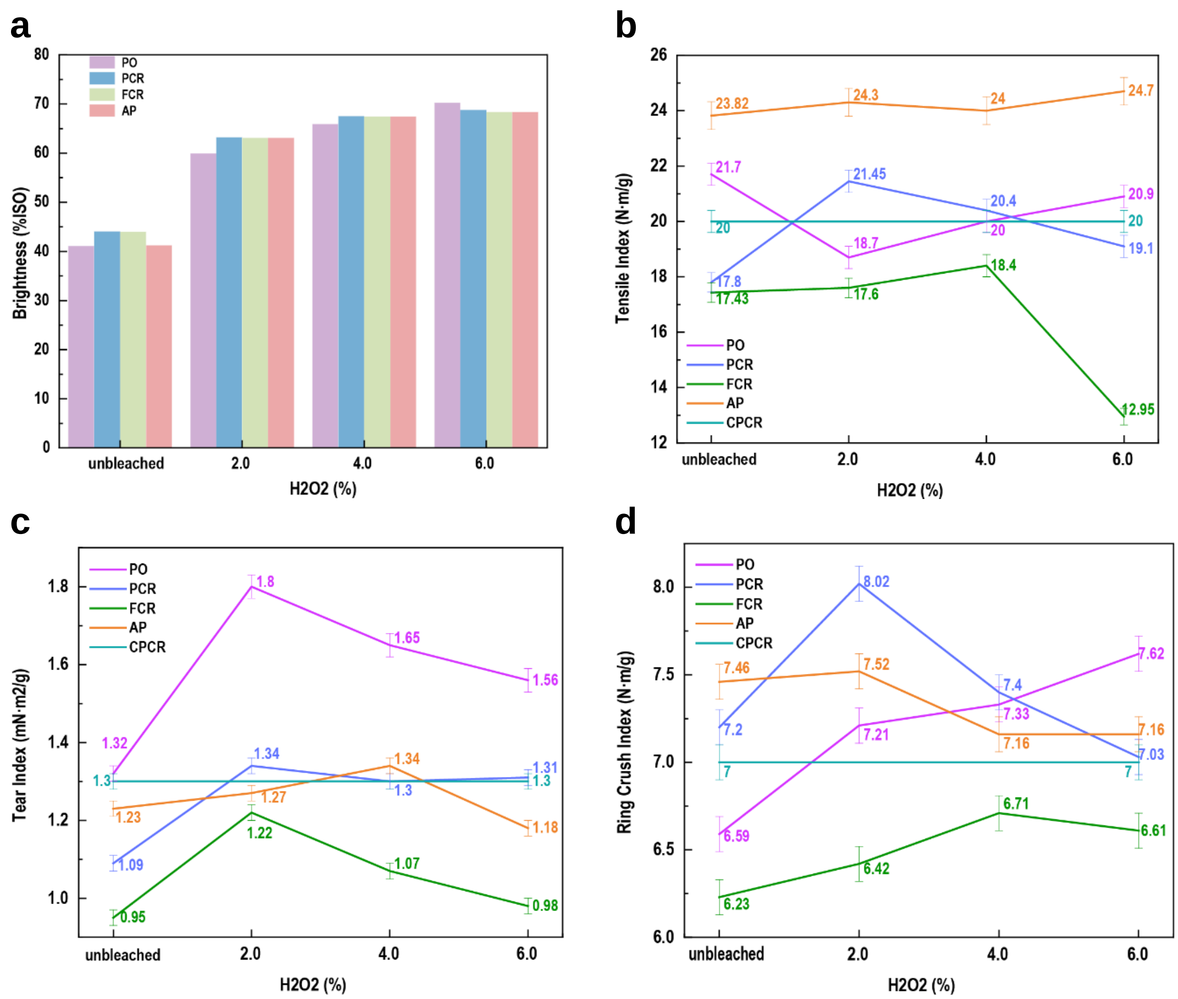

Fig. 1. Whiteness (a), tensile index (b), tear index(c), and ring crush index (d) of pulp handsheets made from CTMP pulps from PO, PCR, FCR and AP (CPCR is commercial paper.)

CONCLUSIONS

A comparative study on chemithermomechanical pulp (CTMP) of four common hardwood species in northern China was conducted. The CTMP pulp from these woods varied significantly in terms of fiber length, fiber width, and whiteness, as well as physical properties. For unbleached pulp, PCR and FCR exhibited the highest whiteness, while AP demonstrated excellent tensile, tear, and burst strength. For bleached pulp using hydrogen peroxide, PO reached the highest whiteness, and AP continued to show the best physical strength. Notably, PO exhibited remarkable bulk of 3.6 cm^3/g and is ideal for low-page-count books.

ACKNOWLEDGMENTS

The work was supported by Science and Technology Department of Shandong Province (YDZX2024140). Shandong Tianhe Paper Co., LTD also provided financial support.

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Article submitted: January 8, 2025; Peer review completed: February 8, 2025; Revised version received and accepted: March 6, 2025; Published: March 26, 2025.
DOI: 10.15376/biores.20.2.3604-3611