

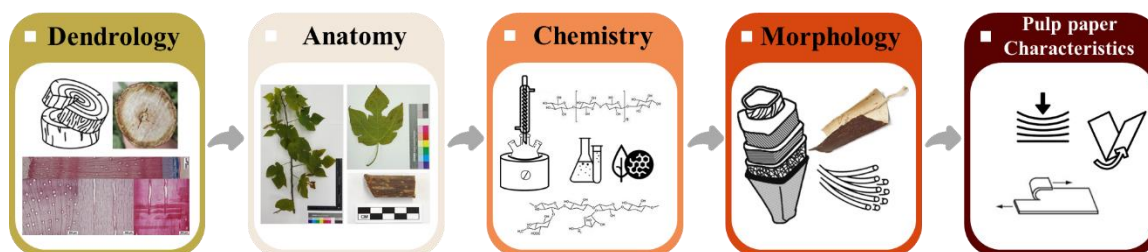
Characteristics of Bast Fibers Derived from the Bark of Three Paper-Mulberry Cultivars in Korea

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GRAPHICAL ABSTRACT



Characteristics of Bast Fibers Derived from the Bark of Three Paper-Mulberry Cultivars in Korea

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Bast fiber from paper-mulberry (*Broussonetia papyrifera*) has long been utilized for handmade paper in Asia, serving as a prominent non-wood cellulose material. When restoring paper cultural assets, selecting a similar paper to the original ensures longevity and prevents deterioration issues like warping or tearing. The production of handmade paper involves several processes, including refining, steaming, and bleaching of raw materials. Once formed into sheets, the physical properties of the paper are dictated by these materials and remain unchanged unless the paper is newly made. Handmade paper production is labor-intensive and time-consuming, emphasizing the need for careful raw material selection to match desired characteristics. This study evaluated the dendrological, morphological, anatomical, and chemical compositions of three paper-mulberry wood types cultivated in Korea and inferred their suitability as pulp for papermaking or repair of archival paper specimens. Paper-mulberry wood showed differences in fiber length according to molecular phylogenetic characteristics, but there were no differences in anatomical characteristics owing to the immaturity of the wood. This study investigated the characteristics of the bast fibers from the bark of paper-mulberry trees with different genetic traits to identify favorable factors likely to affect the pulp and papermaking process and paper quality.

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Keywords: Handmade paper; Korean paper-mulberry; Paper-based cultural heritages; Bast fiber; Paper quality

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INTRODUCTION

Wood bark is generally classified as a byproduct of wood processing or pulping and is often utilized as a fertilizer or fuel for incineration. In contrast, the bast fiber of paper-mulberry wood has been used as a raw material for handmade paper production in Asia, including Korea, China, and Japan, since ancient times. Paper-mulberry is widely distributed across Asian countries and is esteemed as a non-wood cellulosic material because of its high productivity, fast growth, and relatively easy propagation. It has been reported that biomass components with excellent application potential are isolated not only through pulp production (Wada *et al.* 2000), but also through nanofiber preparation (Suarez *et al.* 2022) and biocomposite materials (Neiva *et al.* 2018). These recent studies

demonstrate the high potential value of mulberry bast fibers for a diverse range of product applications (Cultural Heritage Administration. Statistical information 2023).

Paper is one of mankind's greatest inventions and the most essential recording medium connecting history and culture to the present. The discovery of cellulose fiber's papermaking properties dates back over 2,000 years in China, where plant fibers were pulped and formed into sheets. This technology later spread to Japan through Korea, with adaptations to suit each region's needs. East Asia boasts numerous ancient cultural treasures, particularly in Korea, where paper-based artifacts such as transcripts, books, and paintings designated as important cultural assets have increased by 1923% between 2008 and 2022 (UNESCO 2024). Materials used in repairing these paper cultural assets are carefully chosen to match the original paper's quality, fiber composition, thickness, color, and pattern, depending on the artifact type (Ferreira *et al.* 2017). In particular, handmade paper crafted using traditional Korean methods is primarily made from paper-mulberry. It typically utilizes stems that have grown in the most recent year. These are usually grown as shrubs, producing stems with the ideal diameter for papermaking. The paper-mulberry is a deciduous broadleaf shrub belonging to the *Moraceae* family, and when mature, it reaches a height of more than 3 m.

In Korea, paper-mulberry is not an exact scientific name, but is used as a common name referring to the *Broussonetia* genus in all *Moraceae* families. According to recent research, three types of paper-mulberry have been identified as being cultivated in Korea, and *B. kazinoki* × *B. papyrifera* (in this study, referred to as Hybrid-1) is the main raw material for traditional Korean handmade paper. The others are *B. papyrifera* × *M. alba* (referred to as Hybrid-2 in this study) and *B. kazinoki*.

The diverse properties of handmade paper depend on the distinct characteristics of the material used, such as bast fibers. These fibers are derived from the inner bark of certain dicotyledons, including flax, hemp, kenaf, and paper-mulberry. Moreover, the composition of the bark of each tree varies from species to species because it is a complex cellular tissue containing various proportions of phloem, periderm, and rhytidome. This complexity requires demanding and specific characterization of the fiber dimensions and anatomical, morphological, chemical, and physical properties to exploit its full potential and establish appropriate pathways. Fiber characteristics, including size and shape, significantly influence paper properties and manufacturing methods (Go *et al.* 2021). Chemical characterization is vital for determining suitability for various applications and manufacturing processes. The findings of the present study could offer indicators for evaluating potential conversion yield and process economics through component analysis (Hossain *et al.* 2022).

This study analyzed the dendrological, morphological, anatomical, and chemical compositions of three representative paper mulberry trees cultivated in Korea, and further inferred the likely suitability of those fibers for pulp and paper applications.

EXPERIMENTAL

Materials

Three 1 year-old paper-mulberry wood types were selected based on the molecular phylogenetic classification of a previous study (Go *et al.* 2021). These included Hybrid-1 (*B. kazinoki* × *B. papyrifera*), Hybrid-2 (*B. papyrifera* × *M. alba*), and *B. kazinoki*, which are commonly cultivated in Korea (Table 1). Samples were prepared by isolating bark

(including black bark as shown in Table 1) from 1 year-old stems from paper-mulberry trees.

Table 1. The Materials of Paper-Mulberry Used in this Study were Based on Molecular Phylogenetic Classification Obtained in a Previous Study

Abbrevia- tion	GM	GC	GA	GU	JD	JI1	JI2	GG
Classifica- tion	Hybrid-1	Hybrid-2	Hybrid-1	Hybrid-1	Hybrid-1	Hybrid-1	<i>B. kazinoki</i>	Hybrid-1
								

External Phenotype Extraction

Macroscopic observations were conducted to examine the structural features of plant organs (Lee 2002). Vegetative organs (such as stems and leaves), as well as reproductive organs (such as flowers and fruits), were visually confirmed. Leaf arrangement, shape, apex, base, size, and the presence or absence of a sheath were confirmed. Information on the external form of the plant was obtained with the naked eye in 2018, and the floral morphology and reproductive structure of some samples were observed macroscopically in 2019.

Microscopic Observations of Three Different Sections of Wood

Eight mulberry wood samples were cut to approximately 1 to 2 cm and softened in a 1:4 (v:v) mixture of glycerin and distilled water for 5 d at a temperature of 100 °C or higher using a reflux condenser. Each sample was then divided into cross, tangential, and radial sections. The samples were subsequently sliced into 20 to 30 µm-thick sections using a sliding microtome.

For cell observation, the cut slices were stained with 1% safranin aqueous solution, followed by sequential dehydration using 30%, 50%, 70%, and 100% ethanol to make permanent preparations. The prepared permanent preparation specimens were then examined using optical microscopy (© ECLIPSE Ni; Nikon, Japan) at 100 × magnification.

Proximate Chemical Analysis

Standard TAPPI methods were used to measure various parameters including 1% NaOH extraction TAPPI T212-om-02 (2002), alcohol–benzene solubility KS M 7039, holo-cellulose TAPPI T9 wd-75 (1975), α-cellulose KS M 7044, lignin KS M ISO 302, and ash KS M ISO 1762 contents of the paper-mulberry woods.

Fiber Dimensions and Derived Values (indices)

Eight stems of each paper-mulberry type aged less than 1 year were manually debarked. The long bast fiber was segmented upper, middle, and lower (near root part), centered on the root, each cut into approximately 8 cm samples.

Next, 100 mL of 30% nitric acid (60%, Kanto, Japan) and 5 g of potassium chlorate (99%, Sigma Aldrich, USA) were mixed, and the bast fibers were separated into fibers with Schulze solution.

For fiber analysis, the sample underwent maceration in Schulze's solution for 5 h at room temperature (23 to 25°C), followed by thorough washing with distilled water and shaking for dissociation. After staining the dissociated fibers with 1% safranin solution, the fiber length and width were measured using an optical microscope (ECLIPSE Ni, Nikon, Japan).

For the fiber width, lumen width, and cell wall thickness measurements, the bast fibers were immersed in distilled water for 24 h. Subsequently, polyethylene glycol (PEG; #2000, Samchun, Korea) was prepared in a 1:3 (wt%) ratio with distilled water and used for embedding for another 24 h. The embedded sample was sectioned (10 to 20 µm thickness) using a microtome, stained with a double staining solution (1% safranin + 1% astra blue), and measured using an optical microscope (© Nikon ECLIPSE 80i, Nikon, Japan).

The fiber length and width were measured 100 times each by dividing the collected inner bark into top, middle, and basal parts. For a comparative analysis, the trimmean function in MS Excel (Microsoft Corp., Redmond, WA, USA) was used to reduce the error range and calculate the average value. The array was set to 100, the maximum and minimum percentages were set to 0.1%, and average values were calculated. Measurements were taken 100 times in both horizontal and vertical directions at the top, middle, and base of the sample to account for variations in the fiber lumen shape. The average value was calculated using the trimmean function.

Equations

RR, SR, FC, and RC values representing the fiber characteristics were obtained from the fiber length, fiber width, and lumen width using Eqs. 1 to 4 as follows.

$$\text{Runkel ratio (RR)} = 2 \times \text{Cell wall thickness} / \text{Lumen diameter} \quad (1)$$

$$\text{Slenderness ratio (SR)} = \text{Fiber length} / \text{Fiber diameter} \quad (2)$$

$$\text{Flexibility coefficient (FC)} = \text{Lumen diameter} / \text{Fiber diameter} \quad (3)$$

$$\text{Rigidity coefficient (RC)} = 2 \times \text{Cell wall thickness} / \text{Fiber diameter} \quad (4)$$

RESULTS AND DISCUSSION

Dendrology Characteristics

Representative characteristics of the collected mulberry leaf blades are shown in Fig. 1. The hybrid type has lobed leaves, whereas the *B. kazinoki* type has ovate-shaped leaves. Most leaves are lobed, but ovate forms are mixed, and it has been reported that mulberry trees mutate these characteristics as they adapt to local environmental factors (Hossain *et al.* 2022, Kang *et al.* 2013). In samples with ovate leaves, the phyllotaxis was alternate and unifoliate. The leaf apex was pointed, and the base of the leaf was cordate. An investigation of the inflorescence of this sample revealed it to be an indeterminate type, characterized by flowers blooming only on the sides or a portion of the inflorescence, known as a spike. It was confirmed to be a monoecious plant with spherical female inflorescences blooming on the axil of a new branch and male inflorescences hanging

below them (Fig. 1). This characteristic is consistent with previous research results, such as those of molecular phylogenetic studies (Ilvessalo-Pfäffli 1995). The most significant dendrological characteristics of the hybrid and *B. kazinoki* were the differences in leaf shape, number of lobes, and length of the leaf base (Table 2).

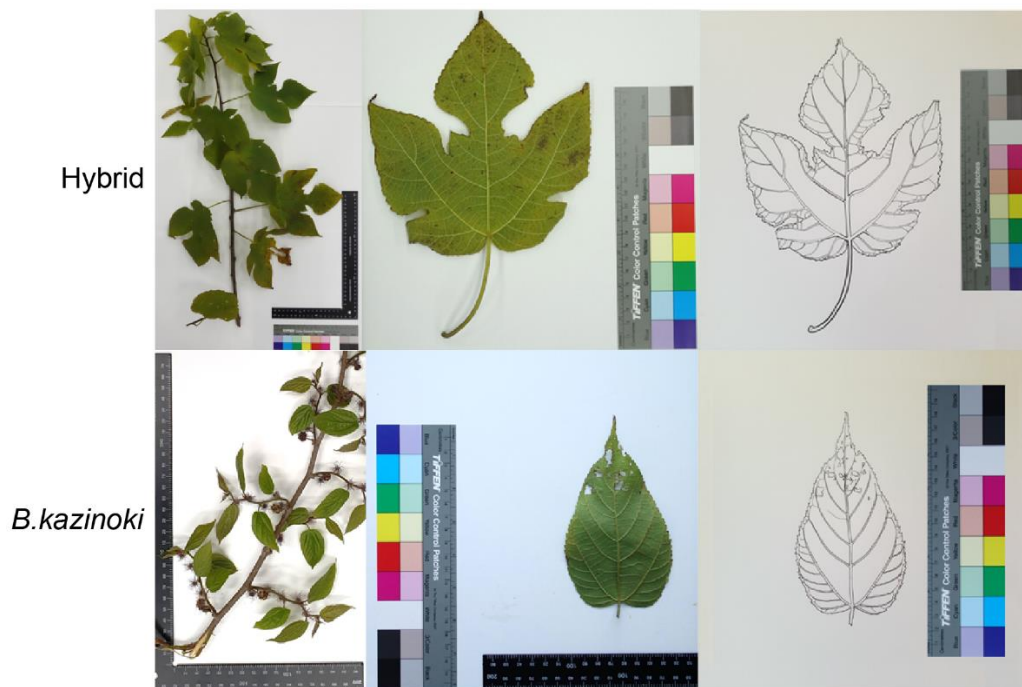


Fig. 1. Shapes of paper-mulberry leaf blade

Table 2. Dendrological Characteristics of Leaf Samples

Abbreviation	Shape	No. of lobes	Petiole length (cm)	Average of leaves (cm)			
				Length		Width	
				Lobed	Ovate	Lobed	Ovate
GM	Lobed	7	9.3	15.5	-	14.8	-
GC	All lobed	7	7	28.0	-	19.5	-
GA	Lobed	7	6.1	18.5	-	15.2	-
GU	Lobed	7	5.8	15.3	-	14.7	-
JD	Lobed < Ovate	3	10.4	13.3	-	10.3	-
JI1	Lobed + Ovate	3	3.8	13.3	-	10.1	-
JI2	Ovate	-	1.4	-	13.0	-	12.8
GG	N.D.						
Abbreviations are shortened regional names; GM: Mungyeong-si, Gyeongsangbuk-do, GC: Cheongsong-gun, Gyeongsangbuk-do, GA: Andong-si, Gyeongsangbuk-do, GU: Uiseong-gun, Gyeongsangbuk-do, JD: Dongchon-li, Jeonbuk-do, JI1: Imsil-gun, Jeonbuk-do, JI2: Imsil-gun, Jeonbuk-do. N.D.: no data							

Anatomic Characteristics

The results of anatomical observations of three different sections of mulberry trees are presented in Fig. 2.

All samples were identified as either ring porous wood or semi-ring porous wood. The majority of vessels appeared as solitary pores, with some showing 2 to 3 multiple pores

arranged radially. Smaller vessels were mostly pore groups, and the axial xylem parenchyma was vasicentric, resembling the paratracheal parenchyma. The medullary ray of the tangential section had 1 to 3 rows, and axial xylem parenchyma and parenchyma were identified around the vessel. Helical thickening was commonly observed in small vessels and intervascular pitting (an alternative form of pitting) was observed in Hybrid 1 (Fig. 2). In radial sections, multirow portions consisted of procumbent cells, with upright or square cells arranged in one row along the upper and lower edges, or in two to three rows in some cases. Prismatic crystals were commonly observed within procumbent or square cells, and vessel member perforation plates exhibited a simple structure. Ray vessel pitting exhibited oval and angular shapes. All eight paper-mulberry samples exhibited similar anatomical characteristics. Because paper-mulberry trees are collected and used from immature paper-mulberry trees less than 1 year old during the traditional Korean handmade paper-manufacturing process, it is assumed that their anatomical characteristics are not significantly different.

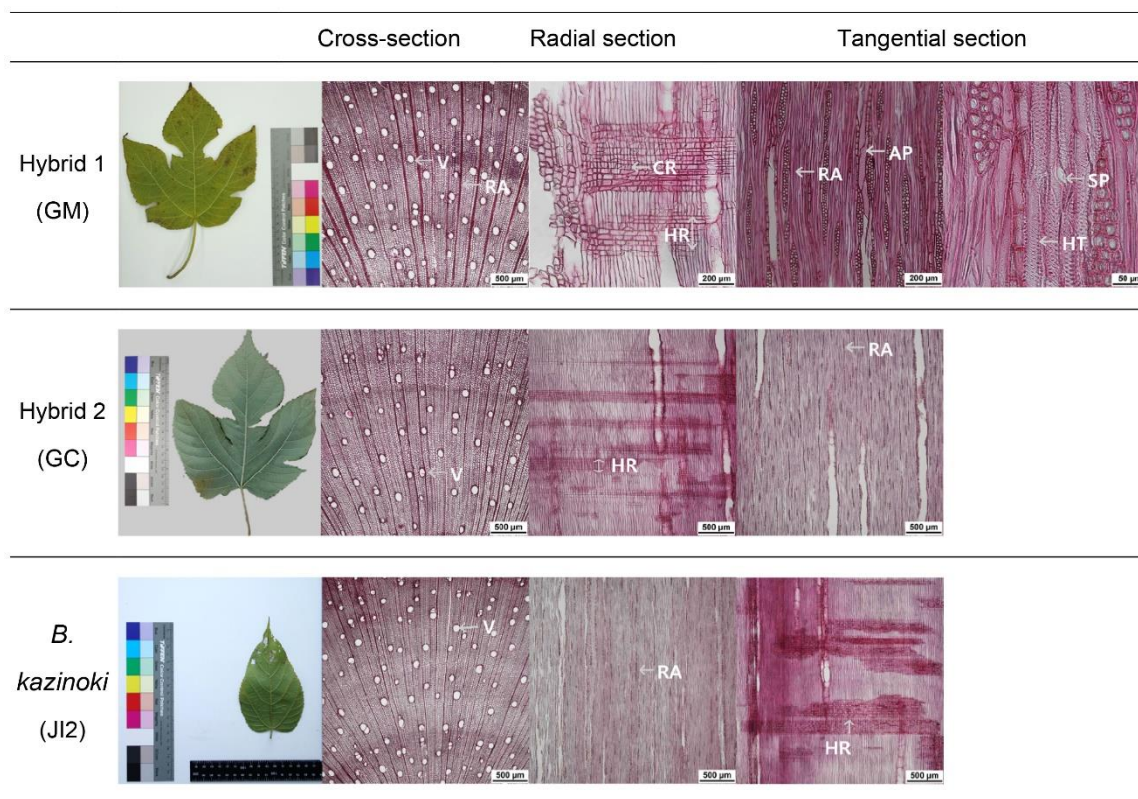


Fig. 2. Typical anatomical characteristics of three types paper-mulberry (JV: vessels, RA: ray, HR: heterogenous ray tissue, AP: alternate pitting, SP: simple perforation plates, HT: helical thickenings, CR: crystals)

Chemical Characteristics

The traditional Korean paper (Hanji) manufacturing process utilizes lye to produce white bast fibers, selectively removing non-cellulosic components. In terms of chemical composition, higher cellulose content and lower levels of alkali and alcohol-benzene extract components indicate superior raw material quality (Gustavsson 2006). Therefore, in a general papermaking process, if the content of the extractive components is high, the pulp yield is reduced, and the consumption of cooking chemicals increases. Additionally,

increased abundance of inorganic substance burdens the process, potentially diminishing pulp yield and paper strength as ash content rises. High lignin levels during paper production can lead to weakened paper strength and yellowing.

The moisture content of the bast fibers in all samples ranged from 7.3% to 10.2% (Table 3). The holocellulose content of these fibers was notably higher than the previously re-reported values, ranging from 71.9% to 84.7%. For comparison, holocellulose content in broad-leaved trees typically ranges from 71 to 84%, while in mulberry trees, it has been reported at 74.2% (Choi and Kim 1999; Kang and Kim 2007). Holocellulose is composed of polysaccharides of α -cellulose and hemicellulose. In JI2 samples, the hemicellulose content was relatively high. Hemicellulose surrounds cellulose microfibrils within plant cell walls, offering structural support. The low extract content and relatively high holocellulose and α -cellulose contents of GC samples suggest that they are optimal for handmade manufacture processing. The standard error of the chemical composition tended to be relatively high, ranging from 0.1 to 11.6, which is thought to be due to the use of bark containing black bark.

Table 3. Chemical Composition Content of Paper-Mulberry

Chemical Composition (%) $\pm$ standard error	GM	GC	GA	GU	JD	JI1	JI2	GG
Moisture content	8.1 $\pm$ 0.1	7.8 $\pm$ 0.1	9.8 $\pm$ 0.1	10.2 $\pm$ 0.1	8.3 $\pm$ 0.3	9.3 $\pm$ 0.1	7.3 $\pm$ 0.4	7.3 $\pm$ 0.1
EtOH-C ₆ H ₆ extracts	10.1 $\pm$ 0.4	10.5 $\pm$ 1.0	10.2 $\pm$ 0.3	10.7 $\pm$ 0.0	17.5 $\pm$ 0.3	9.7 $\pm$ 0.2	14.0*	9.3 $\pm$ 0.8
Holocellulose	81.4 $\pm$ 0.0	83.6 $\pm$ 1.0	84.7 $\pm$ 0.2	82.7 $\pm$ 0.9	75.5 $\pm$ 3.8	79.2 $\pm$ 0.6	81.2 $\pm$ 0.7	71.9 $\pm$ 3.0
α -cellulose	81.7 $\pm$ 1.6	82.8 $\pm$ 0.6	77.7 $\pm$ 3.1	81.1 $\pm$ 4.1	76.6 $\pm$ 0.6	81.7 $\pm$ 0.7	72.4 $\pm$ 1.4	79.7 $\pm$ 0.4
Lignin	4.1 $\pm$ 0.8	11.1 $\pm$ 1.2	10.3 $\pm$ 1.1	10.4 $\pm$ 0.4	12.1 $\pm$ 10.9	11.6 $\pm$ 4.0	22.8 $\pm$ 11.6	2.3 $\pm$ 0.3
Ash	4.7 $\pm$ 0.1	4.8 $\pm$ 0.1	4.8 $\pm$ 0.2	5.4 $\pm$ 0.1	7.3 $\pm$ 0.3	4.9 $\pm$ 0.1	5.7 $\pm$ 0.1	5.6 $\pm$ 0.0

*The sample was measured only once due to insufficient sample volume

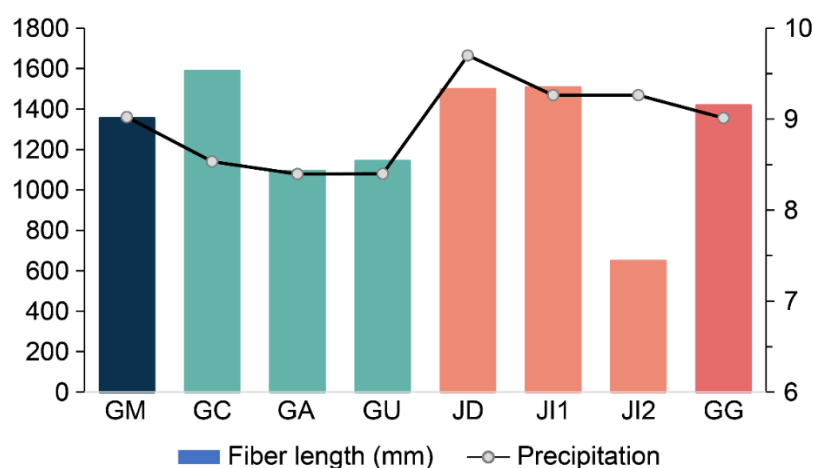
Morphological Characteristics

All samples exhibited a trend of decreasing fiber length from lower to upper, with the lower section having the longest fibers, followed by the medium and upper sections (Table 4). Previous reports indicate that longer fiber lengths contribute to increased folding and tear strengths in paper. Thus, it is inferred that handmade paper crafted from the lower fibers will possess relatively robust tear and folding strength (Ilvessalo-Pfäffli 1995; Lee 1996). The fiber length ranged from 7.4 mm to 9.9 mm, with the JI2 sample having the shortest fiber length but the thickest fiber walls of 23.6 μ m. Consequently, if the JI2 sample were used for papermaking, the resulting paper would have low strength, bulk, and high water absorption owing to its short fiber length and thick fiber walls (Choi and Kim 1999).

Additionally, for the same types of paper-mulberry trees, variations in fiber width and length may occur based on climate and soil quality. Therefore, the environmental impact was evaluated by determining the relationship between precipitation and fiber length. For most samples, the fiber length tended to be proportional to the increase or decrease in precipitation. However, it was noted that the GC sample, representing Hybrid-2, had longer fiber lengths, whereas the JI2 sample (representing *B. kazinoki*) had substantially shorter fiber lengths than was expected based on precipitation levels. This fiber length tendency was confirmed to be a molecular phylogenetic characteristic, rather than an environmental influence (Fig. 3).

Table 4. Analysis of Variance for Fiber Morphology in the Bast Fibers of Paper-Mulberry (U: upper, M: middle, L: lower)

Sample	Length (mm)	Average Length (mm)	Fiber width (μm)	Lumen width (μm)	Cell wall thickness (μm)
G M-U	7.38	8.78	17.88	5.71	6.09
GM-M	8.09		18.45	6.85	5.80
GM-L	10.87		21.49	6.31	7.59
GC-U	8.43	9.37	17.18	7.43	4.88
GC-M	9.37		19.85	7.80	6.03
GC-L	10.30		19.97	7.95	6.01
GA-U	7.99	8.21	18.89	5.66	6.62
GA-M	8.25		18.19	5.87	6.16
GA-L	8.38		18.07	6.75	5.66
GU-U	7.61	8.65	18.95	5.37	6.79
GU-M	9.07		19.39	8.96	5.22
GU-L	9.27		21.58	8.07	6.76
JD-U	8.50	9.19	17.35	6.30	5.53
JD-M	8.63		17.33	10.55	3.39
JD-L	10.43		20.57	10.78	4.90
Jl1-U	8.72	9.93	21.98	7.85	7.07
Jl1-M	10.31		23.14	8.27	7.44
Jl1-L	10.76		26.23	8.46	8.89
Jl2-U	6.59	7.42	19.95	8.91	5.52
Jl2-M	6.60		23.98	8.12	7.93
Jl2-L	9.08		26.79	8.18	9.31
GG-U	8.26	9.52	22.52	8.33	7.10
GG-M	10.11		22.78	10.02	6.38
GG- L	10.19		23.15	10.45	6.35

**Fig. 3.** Relationship between precipitation and fiber length

Pulp Paper Properties

The Runkel ratio (RR), slenderness ratio (SR), flexibility coefficient (FC), and rigidity coefficient (RC) values that are used to predict the pulp papermaking process characteristics are listed Table 5.

RR is considered an important characteristic in pulp and paper processing (Ekhuemelo and Udo 2016). A fiber with an RR value below 1.0 is considered to have a thin cell wall, typically resulting in superior mechanical strength (Sadiku *et al.* 2016). Conversely, RR values exceeding 1.0 yield stiffer, less flexible, and bulkier paper with reduced bonded areas (Dutt and Tydgi 2011). For instance, the JD sample, characterized by the thinnest cell wall, exhibited an RR value of 1.1, indicating superior mechanical strength potential when used in papermaking.

The SR value, representing the fiber length-to-width ratio, is essential for assessing the suitability of papermaking fibers. Fibers with an SR value of 33 or higher are generally deemed suitable for paper-manufacturing. Paper-mulberry fibers are known for their elongated length. Among the samples, JI2 displayed the shortest fiber length but achieved a maximum SR value of 315, whereas the JD sample, boasting the longest fiber length and width, attained a maximum value of 498.

The FC value is an indicator of the degree of fiber bonding. A high value allows the fibers to easily fold and results in excellent surface contact and fiber-to-fiber bonding, producing paper with excellent tensile strength, bursting strength, and tear resistance (Ogbonnaya *et al.* 1997). The JD sample exhibited the highest FC value of 0.50 among the samples, indicating the potential to produce handmade paper with superior physical strength.

It has been reported that as the RC value increases, fiber bonding decreases. Notably, the JD sample had the lowest value (0.50), affirming strong fiber bonding, consistent with the observed FC values.

Table 5. Variation in the Derived Morphological Ratios of the Bast Fibers of Paper-Mulberry (U: Upper, M: Middle, B: Bottom)

Sample	Runkel ratio	Slenderness ratio	Flexibility coefficient (%)	Rigidity coefficient
GM	2.08	452	0.33	0.67
GC	1.46	493	0.41	0.59
GA	2.04	447	0.33	0.67
GU	1.79	433	0.37	0.63
JD	1.10	498	0.50	0.50
JI1	1.90	417	0.35	0.65
JI2	1.82	315	0.36	0.64
GG	1.40	417	0.42	0.58

The present study highlights the possibility of producing hand-made paper considering dendrologic, anatomic, morphologic, chemical, and pulp paper properties, depending on the types of paper-mulberry. The present study also evaluated the major factors influencing the quality of handmade paper. However, since paper-mulberry bast fiber is mostly processed in a traditional way rather than a general pulp and paper process, standards for pulp paper-making properties that are suitable for the properties of handmade paper should be proposed. In addition, if the reliability is improved through the collection and analysis of paper-mulberry samples in East Asia, it will present an opportunity to expand the functions and properties of traditional paper and expand the range of customers who wish to use handmade paper for their own purposes.

CONCLUSIONS

1. Among the dendrological characteristics, Hybrid-1 and *B. kazinoki* were effectively classified through the leaf lobe number and petiole length of the paper-mulberry.
2. The observation of the three different sections on anatomical characteristics is not decisive in distinguishing the three types of paper mulberry, However, we confirmed that both the wood diameter and bark thickness are proportional. This suggests that thicker wood diameter yields more infrared fibers. Regarding chemical properties, the hybrid GC sample proved most suitable for paper manufacturing due to its relatively low extract content, high cellulose content compared to other wood and non-wood fibers, and low ash content.
3. The fiber lengths of the Hybrid-2 (GC) and *B. kazinoki* (JI2) samples were inversely correlated to precipitation, indicating suggests a molecular phylogenetic characteristic rather than an environmental factor.
4. Based on morphological characteristics, the JI2 sample is anticipated to yield paper of relatively low mechanical strength, volume, and high absorbency due to its short fiber length and low SR value.
5. Samples that were considered likely to produce robust paper based on pulp and paper characteristics (RR value < 1, SR value > 33, and low RC value) were hybrids JD and GG.

Fiber characteristics, such as size and shape, substantially influence paper properties and manufacturing methods. Identifying favorable characteristics conducive to consistent paper properties can enhance process, potential conversion yield, and economic efficiency.

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REFERENCES CITED

- Choi, H. S., and Kim, T. J. (1999). "Analysis of sludges from wastewater of Hanji production," *Anal. Sc. Technol.* 12(4), 318-325.
- Cultural Heritage Administration (2023). "Statistical information," (https://www.cha.go.kr/html/HtmlPage.do?pg=/seek/search/statistics.jsp&mn=NS_03_07), accessed 11 July 2023.
- Dutt, D., and Tydgi, C. H. (2011). "Comparison of various eucalyptus species for their morphological, chemical, pulp and paper making characteristics," *Ind. J. Chem. Technol.* 18(2), 145-151.

- Ekhuemelo, D. O., and Udo, A. M. (2016). "Investigation of variations in the fibre characteristics of *Moringa oleifera* (Lam) stem for pulp and paper production," *Int. J. Sci. Technol.* 5(1), 19-25.
- Ferreira, J. P., Quilhó, T., and Pereira, H. (2017). "Characterization of *Betula pendula* outer bark regarding cork and phloem components at chemical and structural levels in view of biorefinery integration," *J. Wood Chem Technol.* 37(1), 10-25. DOI: 10.1080/0277-3813.2016.1224248
- Go, I. H., Jo, A. H., Jeong, L., Heo, T. Y., Cho, K., and Choi, T. H. (2021). "Predictive model of geographical origin discrimination of paper mulberry and handmade paper using ICP-AES/MS and multivariate statistical analysis," *J. Cult. Herit.* 49, 222-228. DOI: 10.1016/j.culher.2020.12.004
- Go, I. H., Jo, A. H., Jang, K. J., Park, K. T., Park, S. M., Park, S. J., and Jeong, S. H. (2002). "Morphological characteristics of bast fiber according to the molecular phylogenetic classification of Korean *Broussonetia*," *J. Korea TAPPI.* 5, 55-65. DOI: 10.7584/JK-TAPPI.2022.10.54.5.55
- Gustavsson, C. (2006). *On the Interrelation between Kraft Cooking Conditions and Pulp Composition*, Ph.D. Dissertation, Kungliga Tekniska högskolan Royal Institute of Technology in Stockholm, Sweden.
- Hossain, M. J., Ghosh, R. K., Das, A. K., Nath, S. C., Islam, M. R., Akhter, S., and Rahman, M. S. (2022). "Investigation of the potentiality of five bamboo species in biorefinery through analysis of chemical profiles," *J. Wood Chem. Technol.* 42(3), 204-210. DOI: 10.1080/02773813.2022.2055770
- Ilvessalo-Pfäffli, M. S. (1995). *Fiber Atlas: Identification of Papermaking Fibers*, T. E. Timell (ed.), Springer berlin, Heidelberg, New York. ISBN: 0-387-55392-4
- Kang, H. J., Lee, H. N., and Jeon, C. (2013). "Study on properties of the *Broussonetia kazinoki* Siebold growth in Jeon-buk," in: *Korea Technical Association of the Pulp and Paper Industry 2013 Spring Conference Presentation Papers*, pp. 61. UCI(KEPA): I410-ECN-0101-2014-580-003662800
- Kang, S. H., and Kim, D. Y. (2007). "A study on pyrolytic and anatomical characteristics of Korean softwood and hardwood," *J. Korean Wood Sci. Technol.* 35(6), 31-42.
- KS M 7039-2000 (2000). "Testing method for organic solvent extractives in pulp," Korean Agency for Technology and Standards (KATS) press, Korea.
- KS M 7044 (2016). "Testing method for alpha, beta and gamma cellulose in pulp," Korean Agency for Technology and Standards (KATS) press, Korea.
- KS M ISO 302 (2004). "Pulps – Determination of Kappa number," Korean Agency for Technology and Standards (KATS) press, Korea.
- KS M ISO 1762 (2019). "Paper, board, pulps and cellulose nanomaterials-Determination of residue (ash content) on ignition at 525 °C," Korean Agency for Technology and Standards (KATS) press, Korea.
- Lee, H. R. (1996). "Paper Science," Gwangilmunhawsa, Suwon, Korea, ISBN: 200050-7000280
- Lee, Y. S. (2002). *Modern Plant Taxonomy*, Woosung Publishing, Seoul, Korea, ISBN: 9788982700019
- Neiva, D. M., Araujo, S., Gominho, J., de Cássia Carneiro, A., and Pereira, H. (2018). "Potential of *Eucalyptus globulus* industrial bark as a biorefinery feedstock: Chemical and fuel characterization," *Ind. Crop. Prod.* 123, 262-270. DOI: 10.1016/j.indcrop.-2018.06.070
- Ogbonnaya, C. I., Roy-Macauley, H., Nwalozie, M. C., and Annerose, D. J. (1997).

- “Physical and histochemical properties of kenaf (*Hibiscus cannabinus* L.) grown under water deficit on a sandy soil,” *Ind Crop Prod.* 7(1), 9-18. DOI: 10.1016/S09266690(97)00-034-4
- Sadiku, N. A., Oluyeye, A. O., and Ajayi, B. (2016). “Fibre dimension and chemical characterisation of naturally grown *Bambusa vulgaris* for pulp and paper production,” *J. Bamboo Rattan.* 15(1-4), 33-43.
- Suarez, S. G., Tuta, E. C., Santos J. A., and Escobar, S. C. (2022). “Manufacturing, mechanical and morphological characterization of new natural hybrid biocomposite materials of fique-mulberry,” *Mater Res-IBERO-Am J. Mater.* 25. DOI: 10.1590/19-80-5373-mr-2022-0097
- TAPPI T212-om-02 (2002). “One percent sodium hydroxide solubility of wood and pulp,” TAPPI press, Atlanta, GA.
- TAPPI T9 wd-75 (1975). “Holocellulose in Wood,” TAPPI press, Atlanta, GA.
- UNESCO. (2024). “Paper conservation and paper making traditions in East Asia,” *Proceedings of the 6th UNESCO sub-regional symposium on paper conservation, UNESCO, Beijing, China.* Available online (<https://unesdoc.unesco.org/ark:/48-223/pf0000245494>), accessed 21 March 2024.
- Wada, H., Khongseri, B., Sinbuathong, N., and Kobayashi Y. (2000). “Waste water treatment technology for small scale pulp and paper mills in Thailand (Part 2). Preliminary treatment test for waste water from pulp and paper mills from paper mulberry (*Broussonetia papyrifera*) in Thailand,” *Japan TAPPI J.* 54(3), 389-395. DOI: 10.1016/j.carbpol.2014.04.056

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