Effect of Beating Process on Characteristics of Cotton Pulp and its Papermaking Performance

Ying Ni, Juan Wu, Hui Sun, Lingzhong Wan, Xiaonan Deng,* and SiHong Ye *

Two kinds of cotton pulp fibers were used as raw materials to explore the relationship between beating process and cotton fiber properties through Hollander beating, Hollander/PFI beating, and enzyme pretreatment/ Hollander beating. The results showed that the medium consistency beating had a strong effect on the fibrillation of cotton pulp fibers, while the effect on the cutting of fibers was weak. However, the low consistency beating process had a strong cutting effect and a weak fibrillating effect on the fibers. With the increase of beating degree, the average length of cotton fiber decreased, the ratio of fibrillation degree and fine fibers increase markedly. In the range of beating degree from 30 to 60 °SR, the tensile index, folding endurance, and bursting index of cotton fiber-based paper generally increased with the beating degree increasing. Paper sheets produced by blending cotton pulp with hardwood pulp had superior tensile index, bursting index, and tearing index compared to those made from pure hardwood pulp. Furthermore, when the beating degree of the cotton pulp was 60°SR and its addition level was 40%, the resulting paper achieved optimal performance in tensile index, bursting index, tearing index, and folding endurance, yielding the best overall paper properties.

DOI: 10.15376/biores.21.3.7790-7800

Keywords: Cotton fiber; Valley beating; Beating degree; Fiber morphology; Paper property

Contact information: Institute of Industrial Crops, Anhui Academy of Agricultural Sciences, HeFei City, AnHui Province, China, Zip Code: 23000;
** Corresponding authors: xn_deng@foxmail.com; shye8126@163.com*

INTRODUCTION

The application scope of paper is becoming increasingly broader, leading to higher demands for its quality and performance. To meet the requirements of different paper grades, suitable raw materials can be selected based on their inherent characteristics to produce paper-based materials. Cotton fiber, as a high-quality long cellulose fiber, has long been used in the production of specialty papers that require exceptional strength, durability, softness, or cleanliness, such as banknote paper, security paper, high-grade filter paper, medical cotton paper, and fine art paper. Compared to wood pulping, the pulping process of cotton linter is simpler with shorter steps, consuming less energy and fewer chemicals while generating lower environmental pollution, offering certain advantages in the pulping process. Moreover, wood serves not only as a raw material for pulping and papermaking but also as a critical resource for industries such as furniture and construction. Given that wood requires a longer growth cycle compared to cotton, it is imperative to maximize the utilization of cotton fiber resources (Lu *et a*l.2023). In the papermaking industry, cotton fiber is categorized as a seed-hair fiber material. Compared to other types of plant fibers, it exhibits unique morphological characteristics such as fine and elongated fibers, relatively smooth cell walls, absence of cross striations and pits, and a distinct lumen. Moreover, cotton fiber has a cellulose content exceeding 90%, making it the natural fiber with the highest cellulose content, and its average degree of polymerization ranges from 10,000 to 15,000 (Pan *et al*. 2010; Li *et al*. 2011). Cotton fibers have a longer average length than hardwood fibers, bamboo fibers, and sisal fibers (Nautiyal *et al*. 2025). The unique structure of cotton fibers make it difficult to fibrillate the fibers. Beating serves as an effective method to enhance the fibrillation degree of cotton fibers. While cooking causes little change in the apparent fiber length, mechanical beating disentangles and cuts the long, intertwined fibers (Wang *et al*. 2006). This mechanical treatment modifies the fiber surface, transforming it from smooth to rough, which significantly enhances inter-fiber bonding capacity (Fišerová *et al*. 2019; Dölle *et al*. 2021; Miao Fei *et al*. 2022). During the beating process, mechanical forces from the beating blades, friction between fibers, velocity gradients within the fluid, and friction between fibers and the beating equipment collectively cause deformation and displacement of the fiber cell walls, disruption and removal of the primary wall and outer secondary wall, and fiber hydration swelling and fibrillation. Transverse cutting, shearing, and abrasive actions on the fibers also occur (Ma 1997). By subjecting cotton fibers to beating, the number of free hydroxyl groups in cellulose is increased, which enhances the water absorption and swelling degree of the cotton fibers. This leads to reduced internal cohesion and a more relaxed fiber structure, thereby improving fiber softness and plasticity. As a result, the degree of fibrillation rises, increasing the specific surface area of the fibers (Huo *et al*. 2025). These changes promote inter-fiber bonding and ultimately improve their paper-forming performance. (Wang *et al*. 2006; Yuan *et al*. 2017).

Cotton linter refers to the short fibers remaining on the gin-run cottonseed device after ginning. These are stripped from the seed surface by a delinting machine (Chen *et al*. 2011). It is primarily classified into three types based on fiber length: first-cut linters have fibers longer than 13 mm; second-cut linters (also known as double cashmere cotton) have fibers no longer than 13 mm, with fibers of 3 mm or shorter accounting for no more than 58% of the total fiber mass; and third-cut linters also have fibers up to 13 mm in length, but here, the 3 mm or shorter fibers make up 58% or more of the total mass. The impurity content of cotton linter is generally 6% or higher (GB/T 20223. 2018). Although cotton linter fibers are shorter than those of third-grade cotton, their maturity is not inferior—largely because nutrients are more readily transported into these shorter fibers. Refined cotton linter can have a cellulose content exceeding 98%, while unrefined linter still maintains a cellulose level above 90% (Zhang *et al*. 1992; Li *et al.* 2011). Despite their shorter length and higher impurity content, cotton linters show slightly higher maturity and come at a lower cost. In cotton textile manufacturing, Noil designates the mixture of fibers and impurities separated by machinery such as openers, carders, and combers. This material typically consists of shorter fibers and contains a high level of trash. Despite often being classified as a waste product or by-product of spinning, much of this material holds considerable potential for recovery and subsequent application.

Beating or refining, of pulp fiber is the mechanical treatment and modification of fibers so that they can be formed into paper or board of desired properties. The main target of beating is to improve the bonding ability of fibers so that they form strong and smooth paper sheets with ideal properties for converting and printing (Dölle *et al*. 2021). Refining equipment can be classified into industrial refiners for continuous operation and laboratory equipment for batch operation, such as Hollander beaters (informally called Valley beaters) and PFI mills (Mandlez *et al*. 2022). PFI milling is a batch refining laboratory procedure in which pulp is held against a bedplate using centrifugal force and the spinning refiner rotor is forced against the bedplate imparting a mechanical shearing action on the fibers (TAPPI 2008). Hollander beating is a batch refining process in which low consistency pulp is looped around a well and forced between a rotor bar and loaded bedplate to generate mechanical shearing action (TAPPI 2001). The effects of beating or refining on fiber modification and fines generation vary significantly depending on the equipment and process parameters employed. Under equivalent drainage resistance conditions, pulp processed through a PFI mill generally demonstrates higher breaking length than that treated by industrial refiners. The mechanical action in PFI refining primarily results from the pulsating impacts of beating bars, which predominantly induce internal fibrillation of fibers. In contrast, industrial refiners not only achieve fiber compaction but also cause substantial fiber shortening and external fibrillation. Both approaches generally promote internal and external fibrillation while generating fines. However, PFI refining shows stronger tendency toward internal fibrillation, whereas industrial refining produces more pronounced external fibrillation, greater fines generation, and more significant fiber cutting (Dölle *et al*. 2021).

In the field of papermaking, enzyme treatment (primarily consisting of cellulase and hemicellulase) has been extensively studied as a biological refining or pretreatment method. Enzymes can be used to modify and/or degrade the lignin and hemicelluloses contents while maintaining the cellulose portion. On the other hand, enzyme helps in restrictive hydrolysis of several elements or selective hydrolysis of specified component in the cellulosic fibers. Proper enzymatic pretreatment can improve pulp drainage properties and enhance paper strength. Thus, cellulase pretreatment has an effect analogous to mechanical beating, thereby helping to reduce energy consumption in the pulping and papermaking process (Saira and Vauhkonen 2024; Frias *et al.* 2024).

There is a substantial body of literature related to systematic investigation of the effects of beating and enzymatic pretreatment on wood pulps (both softwood and hardwood) and non-wood plant fibers such as bamboo pulp and wheat straw pulp. In contrast, the beating characteristics of cotton pulp remain insufficiently studied. This study investigated the relationship between cotton fiber beating processes and fiber characteristics, as well as the influence of beating degree on the performance of cotton pulp paper. Bevis noil cotton pulp and double cashmere cotton pulp were used as raw materials to examine the effects of three different beating processes—Hollander beating, combined Hollander/PFI beating, and enzymatic pretreatment followed by Hollander beating (enzymatic pretreatment/Hollander beating)—on the morphological properties of cotton fibers and the resulting paper-forming performance. The research provides a theoretical foundation for producing high-performance cotton fiber paper. Fiber structural characteristics were characterized by fiber length, fiber width, fibrillation and branching effect, and fines content. Paper performance was characterized by tensile index, burst index, tear index, and folding endurance.

EXPERIMENTAL

Materials

Bevis noil cotton pulp and double cashmere cotton pulp were provided by the Institute of Industrial Crops, Anhui Academy of Agricultural Sciences. Bleached hardwood pulp (beating degree: 35°SR) and endoglucanase (Banzyme™ 2900) were supplied by

UPM-Kymmene Co., Ltd. (Jiangsu, China). Sodium hydroxide (analytical grade) and citric acid (analytical grade) were purchased from Shanghai Runjie Chemical Reagent Co., Ltd.

Equipment

The following equipment was used: water bath constant temperature oscillator (SYC-C, Shanghai Xinmiao Medical Instrument Manufacturing Co., Ltd.), PFI mill (HAMJERN MASKIN 621, Norway), fiber analyzer (MorFi Compact, Techpap, France), Ultrasonic Cell Disruptor (VCX 750, SONICS & MATERIALS, USA), beating degree tester (DJ-100, China), Hand Sheet Machine (MESSMER 255, USA), L&W tensile tester (CE062, Lorentzen & Wettre, Sweden), L&W bursting strength tester (CE180, Lorentzen & Wettre, Sweden), L&W tear tester (009, Lorentzen & Wettre, Sweden), and folding endurance tester (MIT/U21B, USA) were utilized for sample processing and characterization.

Beating

A predetermined mass of Bevis noil cotton pulp and double cashmere cotton pulp was separately processed using three distinct beating methods: Hollander beating, combined Hollander/PFI beating, and enzymatic pretreatment followed by Hollander beating. Hollander beating was conducted at 2% pulp consistency), while PFI beating (within the combined process) employed 10% pulp consistency. For enzymatic pretreatment coupled with Hollander beating, an enzyme dosage of 10 mg/g (Ban zyme™ 2900 endoglucanase) was applied at 50 °C for 2 h. All beating processes were conducted across beating degree gradients of 10, 20, 30, 40, 50, and 60 °SR, where 10 °SR represents the initial state of the cotton pulp.

Fiber Morphological Analysis

The fiber morphology of the cotton fiber samples treated by Hollander beating, combined Hollander/PFI beating, and enzymatic pretreatment followed by Hollander beating were analyzed respectively. The MorFi Compact fiber analyzer was employed to measure parameters including fiber length, fiber width, fibrillated length ratio, and fines length ratio.

Handsheet Making

Hand sheets with a basis weight of 70 g/m² were prepared using cotton fibers processed through three beating methods: Hollander beating, Hollander/PFI beating, and enzymatic pretreatment/Hollander beating. Due to fiber flocculation during sheet formation causing uneven fiber distribution and poor formation in pulps beaten to 10 °SR and 20 °SR, only pulps at beating degrees of 30, 40, 50, and 60 °SR were used for hand sheet making. Additionally, fiber blending was conducted using 60 °SR-beaten cotton fibers mixed with hardwood fibers, with cotton pulp incorporation levels set at 10%, 20%, 30%, and 40% by mass.

Paper Performance Characterization

The laboratory-prepared paper sheets underwent comprehensive physical property testing. Tensile strength (GB/T 22898 2008) was measured using an L&W CE062 tensile tester. Burst strength was determined according to GB/T 454 (2020) with an L&W CE180 burst tester. Folding endurance was evaluated following GB/T 457 (2008) on an MIT/U21B folding endurance tester. Tear resistance was analyzed based on GB/T 455

(2002) using an L&W 009 tear tester, with all specimens conditioned at 23 ± 1°C and 50 ± 2% relative humidity for 24 h prior to testing.

Statistical Analysis

All the experiments and measurements in this study were conducted using three independent repeated experiments (n = 3) to ensure the reproducibility of the results and facilitate statistical analysis. Data are presented throughout the manuscript as the mean value ± standard deviation (SD).

RESULTS AND DISCUSSION

Effects of Different Beating Methods on Cotton Fiber Properties

In the enzymatic pretreatment/Hollander beating sequential process, fiber width increased with elevated beating degrees (Fig. 1b; Fig. 2b). This was potentially attributable to enzymatic action enhancing water absorption and swelling of fibers, compounded by increased fines content that further amplified swelling potential (Zhu *et al*. 2022).

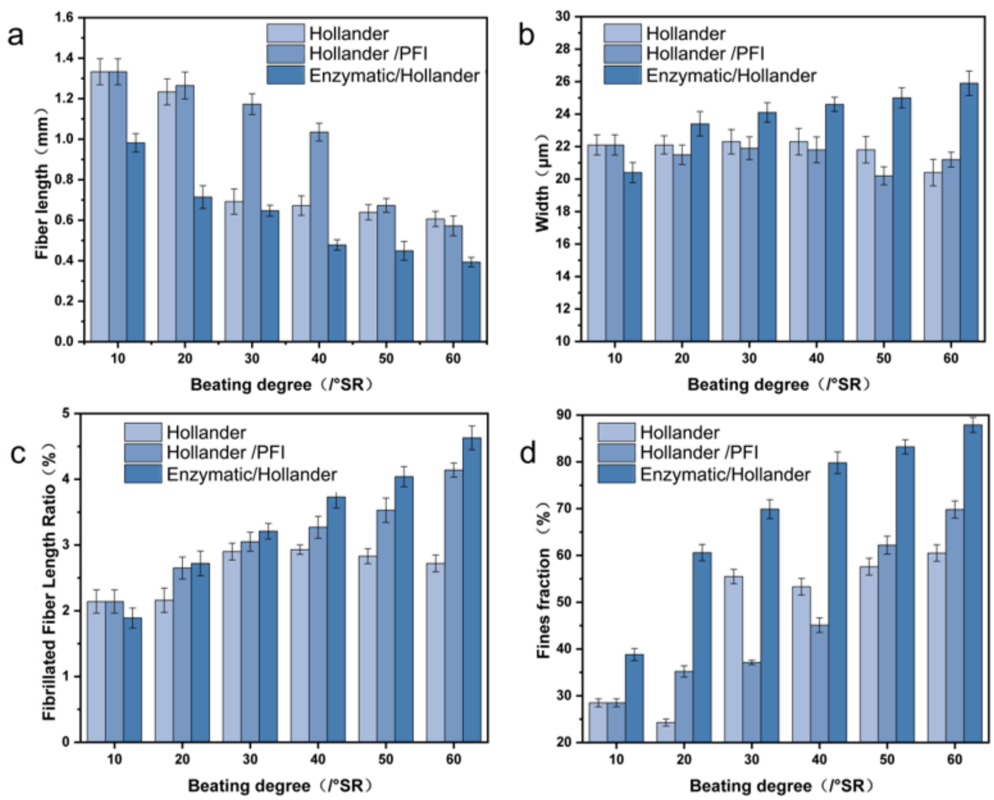

Fig. 1. Fiber characteristic parameters of Bevis noil cotton pulp under different beating methods. (a) Effect of beating degree on fiber length; (b) effect of beating degree on fiber width; (c) effect of beating degree on fibrillated fiber length ratio; (d) effect of beating degree on fines fraction

Employing three different beating methods, fiber length decreased progressively with increasing beating degree. Notably, the rate of length reduction moderated when beating degrees exceeded 40 °SR. Furthermore, Bevis noil cotton pulp consistently exhibited longer fibers than double cashmere cotton pulp (Figs. 1a; 2a). At identical beating degrees, the fiber length hierarchy consistently ranked Hollander/PFI > Hollander > Enzymatic/ Hollander (Fig. 1a; Fig. 2a). This can be attributed to PFI beating's significantly milder cutting action versus Hollander beating's high-shear blades. Therefore, the Hollander/PFI combination better preserved fiber length integrity (Li *et al*. 2022). Combined with enzymatic pretreatment, cotton fiber cell walls were effectively delaminated, rendering them structurally compromised and consequently more susceptible to severe cutting and fibrillation during subsequent Hollander beating, thereby generating substantially higher fines content (Ma *et al*. 2020) (Figs. 1d; 2d).

Increasing the beating degree had little effect on the width of cotton fibers, while the fibrillation length ratio showed a slight increase and the fines length ratio exhibited a significant increase. This indicates that raising the beating degree facilitated fiber fibrillation and increased the proportion of fines. Double cashmere cotton pulp exhibited higher fibrillation length ratios and fines length ratios than Bevis noil cotton pulp. Among the beating methods, Hollander/PFI and enzyme pretreatment/Hollander showed better improvements in fibrillation effectiveness (Figs. 1c; 2c). This is because PFI beating (a type of beating equipment) inherently yields good fibrillation results, while enzymes promote fiber surface activation and loosening, thereby enhancing the fibrillation and branching rate (Li *et al*. 2020).

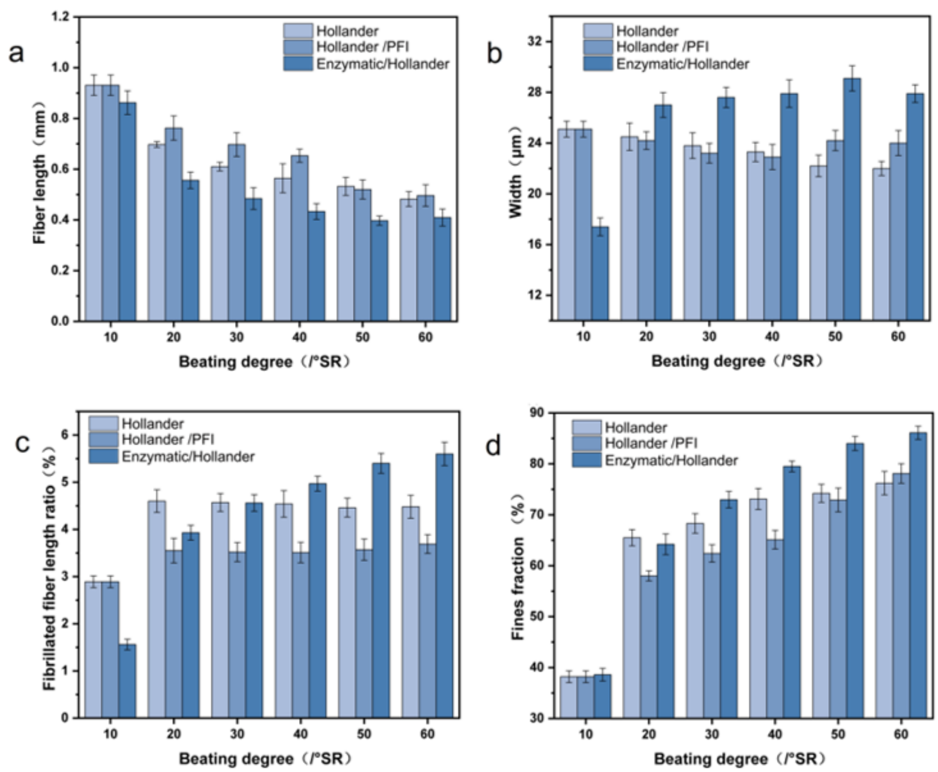

Fig. 2. Fiber characteristic parameters of double cashmere cotton pulp under different beating methods. (a) Effect of beating degree on fiber length; (b) effect of beating degree on fiber width; (c) effect of beating degree on fibrillated fiber length ratio; (d) effect of beating degree on fines fraction

Impact of Beating Degrees on Paper Performance

The tear index initially decreased then increased with rising beating degree. This behavior is governed by fiber length and interfiber bonding forces. At low beating degrees, weak interfiber bonding resulted in strong dependence of tear index on fiber length. However, as the beating degree was increased, greater fiber bonding sites enhanced interfiber bonding strength (Fig. 3b). Consequently, tear index became less dependent on fiber length and was primarily governed by bonding strength, exhibiting a stronger positive correlation with bonding strength at higher beating degrees (Gülsoy *et al*. 2020). Folding endurance is influenced by single-fiber tensile strength. Enzymatically treated cotton fibers exhibited lower single-fiber strength than those processed by the other two methods, resulting in significantly reduced folding endurance of the resultant paper (Fig. 3d). Comprehensive analysis of paper physical properties and fiber characteristics revealed that both Bevis noil pulp and double cashmere cotton pulp achieved optimal paper-forming properties at 60 °SR across Hollander, Hollander/PFI, and enzymatic/Hollander beating methods. This beating degree maximized fibrillation efficacy while maintaining fiber integrity. Consequently, cotton pulp beaten to 60 °SR within the 10 to 60 °SR range is recommended as the optimal blend component for fiber furnishes (Figs. 1, 2, 3).

As shown in Fig. 3, within the beating degree range of 30 to 60 °SR, tensile index, burst index, and folding endurance of cotton pulp papers increased with elevated beating degrees.

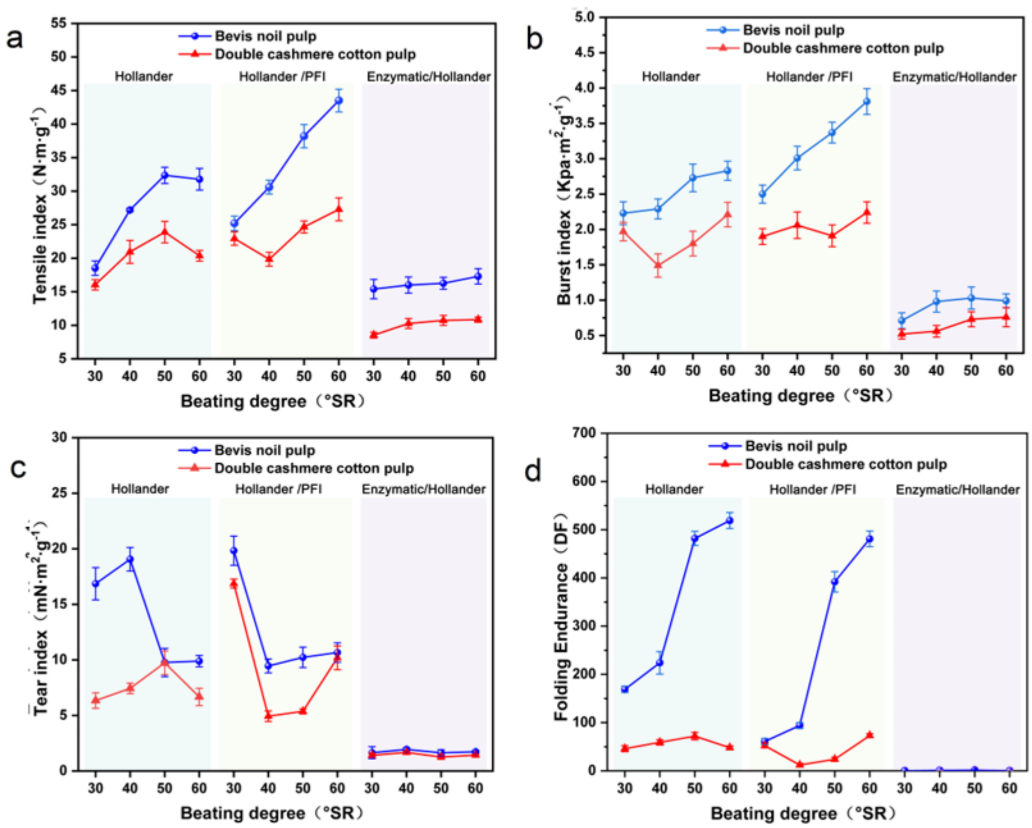

Fig. 3. Paper properties of cotton pulp with different beating degrees. (a) Effect of beating degree on tensile index; (b) effect of beating degree on burst index; (c) effect of beating degree on tear index; (d) effect of beating degree on folding endurance.

Paper performance is primarily governed by interfiber bonding strength. Higher beating degrees promote fiber fibrillation, enhancing formation uniformity and strengthening interfiber bonding forces. Consequently, increased beating degrees improve tensile and burst indices of cotton pulp papers. Owing to superior fibrillation efficiency in PFI refining, the Valley/PFI beating approach yielded higher tensile and burst indices compared to the other two methods. Bevis noil cotton pulp paper consistently outperformed double cashmere cotton pulp in all metrics, which can be attributed to its longer fiber length (Figs. 1a, 2a). At equivalent beating degrees, Bevis noil pulp was relatively longer than double cashmere cotton pulp, resulting in superior physical properties.

Effects of Cotton Pulp Addition Levels on Paper Performance under Different Beating Methods

Factors such as fiber orientation, fiber entanglement, and interfiber bonding strength collectively determine the paper performance (Lu *et al*. 2022). As evidenced in Fig. 4, papers incorporating Bevis noil cotton pulp exhibited superior properties due to longer fiber length and enhanced fibrillation degree. Increasing cotton pulp addition from 10% to 40% progressively improved tensile index, burst index, tear index, and folding endurance. Compared to pure hardwood pulp, cotton pulp exhibits longer fibers and stronger interfiber bonding forces, thus yielding paper with superior performance when blended with cotton fibers.

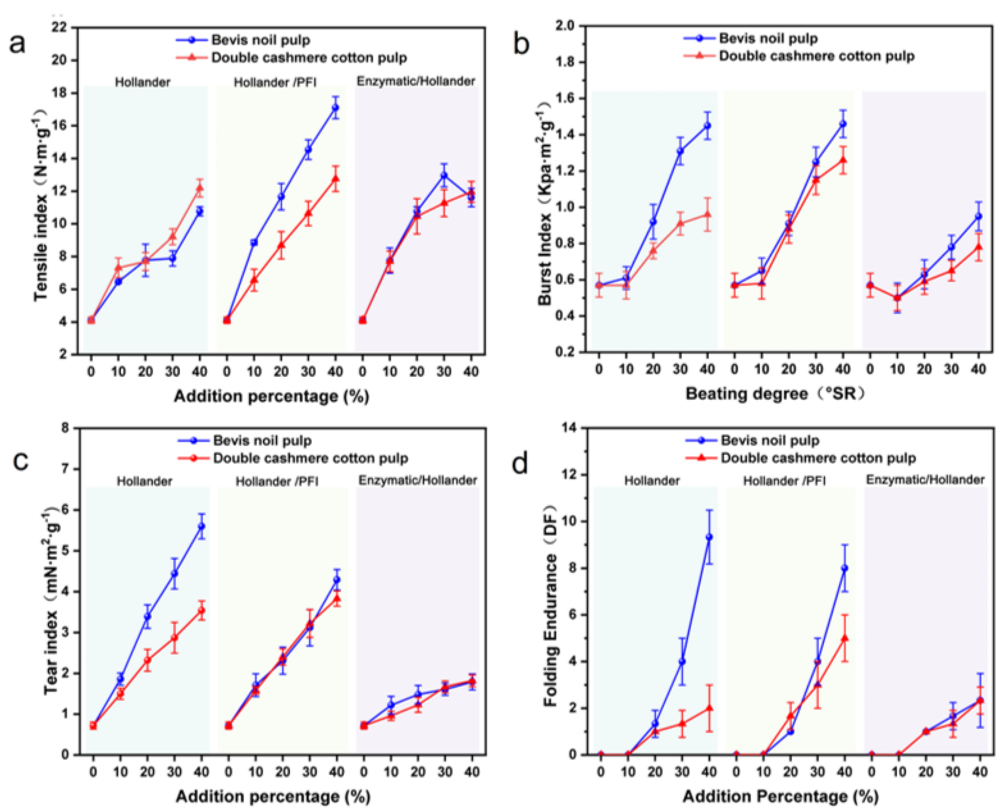

Fig. 4. Effect of cotton pulp addition on paper properties under different beating modes. (a) effect of cotton pulp addition on tensile index; (b) effect of cotton pulp addition on burst index; (c) effect of cotton pulp addition on tear index; (d) effect of cotton pulp addition on folding endurance.

Among the three beating methods, the Valley/PFI approach demonstrated superior outcomes: longer fiber retention, enhanced fibrillation degree, and improved fiber entanglement. Consequently, papers produced with this blended pulp exhibited significantly higher physical properties than those from the other two methods. Conversely, enzymatic pretreatment loosened fiber structures and reduced polymerization degrees, resulting in diminished fiber intrinsic strength and consequently inferior paper performance compared to non-enzymatic approaches.

CONCLUSIONS

1. This study employed three beating methods— Hollander, Hollander/PFI, and enzymatic pretreatment/Hollander —to process Bevis noil cotton pulp and double cashmere cotton pulp. As beating degree increased, both cotton fiber types exhibited progressive reductions in average fiber length, with the degree of length reduction moderating significantly beyond 40 °SR. Concurrently, the fibrillated length ratio showed marginal increases, while the fines length ratio rose substantially. At equivalent beating degrees, fiber length followed this hierarchy: Hollander/PFI > Hollander > enzymatic pretreatment/Hollander.
2. Within the beating degree range of 30 to 60 °SR, both cotton fiber papers exhibited increasing tensile indices, folding endurance, and burst indices with elevated beating degrees, whereas the tear index initially decreases before rising with increasing beating degrees.
3. Compared to paper made from pure hardwood pulp, incorporating cotton pulp fibers significantly enhanced key physical properties of blended sheets, including tensile index, burst index, folding endurance, and tear index. Optimal performance was achieved at 60 °SR beating degree with 40% cotton pulp addition. Notably, sheets blended with Bevis noil cotton pulp outperformed those with double cashmere cotton pulp under identical blending conditions.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Major Science and Technology Special Project of the Xinjiang Uygur Autonomous Region (2023A02001 and 2025A02001), and The Scientific Research Project of Anhui Academy of Agricultural Sciences (No. 2026YL022).

REFERENCES CITED

Chen, J. C. (2011). *Introduction to Linter Pulping*, China Light Industry Press.

Dölle, K., and Bajrami, B. (2021). "Beating of eucalyptus pulp fibers under neutral and alkaline conditions – A valley beater study," *Journal of Engineering Research and Reports* (2021), 86-96. https://doi.org.10.9734/jerr/2021/v20i817362

Fišerová, M., Gigac, J., Stankovská, M., and Opálená, E. (2019). "Influence of bleached softwood and hardwood kraft pulps on tissue paper properties," C*ellulose Chemistry and Technology* 53(5-6), 469-477. https://doi.org.10.35812/CelluloseChemTechnol.2019.53.47

Frias, M., Reynoso, S., Rambhia, S., Noki, G., Olson, J., Stoeber, B., and Trajano, H. L. (2024). "Effect of incubation conditions of cellulase hydrolysis on mechanical pulp

fibre morphology," *Carbohydrate Polymers* 344, article 122529. https://doi.org/10.1016/j.carbpol.2024.122529.
GB/T 454 (2020). "Paper – Determination of bursting strength," Standardization Administration of China, Beijing, China.
GB/T 455 (2002). "Paper and board – Determination of tearing resistance," Standardization Administration of China, Beijing, China.
GB/T 457 (2008). "Paper and board – Determination of folding endurance," Standardization Administration of China, Beijing, China.
GB/T 20223 (2018). "Cotton linter," Standardization Administration of China, Beijing, China.
GB/T 22898 (2008). "Paper and board – Determination of tensile properties – Constant rate of elongation method (100 mm/min)," Standardization Administration of China, Beijing, China.
Gülsoy, S. K., and Uysal, S. (2020). "Effects of recycled fiber fines on hand sheet properties of different unbeaten and beaten pulps," *Drvna Industrija* 71(4), 327-337. https://doi.org.10.5552/drvind.2020.1904
Huo, J., Hu, Z., Shi, L., Su, K., Li, H., and Hu, J. (2025). "A comparative study on the beating performance of three types of cotton pulp: Combed cotton, long-staple cotton, and linter," *China Pulp & Paper* 2025, 1-7.
Li, C., Chen, R., Zhang, X., Xiong, J., Zheng, Y., and Dong, W. (2011). "Fabrication and characterization of electrospun nanofibers of high DP natural cotton lines cellulose," *Fibers Polym.* 12, 345-351. https://doi.org/10.1007/s12221-011-0345-4
Li, J. S. (2020). "The role of biological enzymes in natural color toilet paper pulping," *Heilongjiang Pulp & Paper* 48(4), 5-7. https://doi.org.10.3969/j.issn.1673-0283.2020.04.002
Li, S. L. (2011). "Removal of impurities in the linter pulping process," *China Pulp & Paper* 30(09), 73-75. https://doi.org.10.3969/j.issn.0254-508X.2011.09.017
Li, W. Q., Li, B. Y., Lei, Y. C., Li, H. L., and Hu, J. (2022). "Variations of sisal pulp polymerization degree and fiber length in cooking and beating," *China Pulp and Paper* 41(3), 20-26. https://doi.org.10.11980/j.issn.0254-508X.2022.03.003
Lu, S. Q., Chen, J. Y., Chen, T., Xu, H. Y., and Luo, Y. Y. (2022). "Effect of beating degree and fiber ratio on fiber substrate properties of liquid packaging paperboard surface," *China Pulp and Paper* 41(5), 32-36. https://doi.org.10.11980/j.issn.0254-508X.2022.05.005
Lu, X. (2023). *Study on Influencing Factors and Control of Linter Pulp Color*, Master's thesis, South China University of Technology. https://doi.org.10.27151/d.cnki.ghnlu.2023.005878
Ma, C., Yue, S. P., Li, Y., Zhao, H. F., and Sha, L. Z. (2020). "Effect of enzyme treatment on the performance of fiber refining," *China Pulp and Paper* 39(7), 44-50. https://doi.org.10.11980/j.issn.0254-508X.2020.07.007
Ma, X. (1997). "Comparison and evaluation of chemical pulp treatment by PFI mill and Wally beater," *The 8th Annual Conference of China Paper Society*, 15.
Mandlez, D., Koller, S., Eckhart, R., Kulachenko, A., Bauer, W., and Hirn, U. (2022). "Quantifying the contribution of fines production during refining to the resulting paper strength," *Cellulose* 29, 8811-8826. https://doi.org/10.1007/s10570-022-04809-x
Miao, F., Zhang, M., Yang, R., and Sheng, J. (2022). "Effect of beating on softwood pulp fiber reinforced calcium silicate board," *Cellulose* 29, 4125-4134. https://doi.org/10.1007/s10570-022-04526-5

Nautiyal, S., Dimri, S., Riyal, I., Sharma, H., and Dwivedi, C. (2025). "Natural fibres and their composites: A review of chemical composition, properties, retting methods, and industrial applications," *Cellulose* 32, 3497-3527. https://doi.org/10.1007/s10570-025-06487-x

Pan, Z., Sun, D., Sun, J., Zhou, Z., Jia, Y., Pang, B., Ma, Z., and Du, X. (2010). Effects of fiber wax and cellulose content on colored cotton fiber quality. *Euphytica* 173, 141-149 . https://doi.org/10.1007/s10681-010-0124-0

Saira, O., and Vauhkonen, C. (2024). "Cellulase-assisted refining in a paperboard mill: Avoided emissions from energy savings. A case study of a Finnish paperboard mill," *Cleaner Engineering and Technology* 20, article 100760, ISSN 2666-7908, https://doi.org/10.1016/j.clet.2024.100760.

TAPPI T 200 sp-01 (2001). "Laboratory beating of pulp (Valley beater method)," TAPPI Test Methods. Atlanta, GA, USA.

TAPPI T 248 sp-08 (2008). "Laboratory beating of pulp (PFI mill method)," TAPPI Test Methods. Atlanta, GA, USA.

Wang, C. H., and Wang, Z. J. (2006). "The relationship between cotton pulp beating and fiber properties," *Heilongjiang Pulp & Paper* 2006(4), 8-10. https://doi.org.10.3969/j.issn.1673-0283.2006.04.003

Yuan, G. J., Xue, D., Yuan, Y. L., Cai, W. G., Zhu, Y. F., and Sui, K. (2017). "Effect of pulping process on the bulk thickness of tobacco leaf substrate reconstructed by papermaking method," *China Pulp and Paper* 36(10), 30-36. https://doi.org.10.11980/j.issn.0254-508X.2017.10.005

Zhang, Q. L., Chen, Q. J., and Hu, D. (1992). "Development trends of linter pulping technology," *Tianjin Paper Making*, (01), 1-13+26.

Zhu, Z. W., Li, B. Y., and Li, H. L. (2022). "Comparative study on beating characteristics and paper properties of sulfate bamboo pulp and wood pulp," *China Pulp and Paper* 41(6), 43-50. https://doi.org.10.11980/j.issn.0254-508X.2022.06.007

Article submitted: October 14, 2025; Peer review completed: November 1, 2025; Revised version received: December 19, 2025; Accepted: December 28, 2025; Published: July 7, 2026.

DOI: 10.15376/biores.21.3.7790-7800