The Use of Twin Screw Extruder Instead of Model Screw Device During Bamboo Chemo-mechanical Pulping

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Bamboo is one of the most important raw materials for pulp and paper production in several countries due to its abundance and cost-effectiveness. However, the difficulties in bleaching and low brightness of bamboo chemo-mechanical pulp (CMP) has limited the expansion of its utilization. In this study, the low-cost twin-screw extruder (TSE) was used instead of the high-cost common extruded model screw device (MSD) before chemical impregnation to improve the brightness of the bamboo CMP. There were minor differences in the holocellulose, lignin, and pentose contents in the extruded materials between the two devices. The absorbency of the TSE extruded materials was 4.50 g/g, which was three times that of the material extruded by MSD. Alkali optimization was conducted at levels of 12% H_2O_2. The TSE-CMP achieved the highest brightness, at 57.6% ISO with 6% sodium hydroxide (NaOH), while the MSD-TMP only reached approximately 49.6% ISO with 3% NaOH. At the same time, the physical properties of paper-sheets made from bleached TSE-CMP and MSD-CMP were tested. When bleached at 12% H_2O_2 with 6% NaOH, the tensile index of TSE-CMP was higher compared with that of MSD-CMP, while the other strength properties were nearly unchanged.

Keywords: Bamboo; Twin-screw extruder; Model screw device; Chemo-mechanical pulp; Bleaching

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INTRODUCTION

Due to the shortage of forest resources in Asian countries, non-woods are used extensively in pulp and paper production in several countries because of their abundance and cost-effectiveness. Many studies have been conducted on non-wood pulping in relation to the pulp properties and strategies for improvement (Jahan *et al.* 2007; Fatehi *et al.* 2009a, 2009b; Hosseinpour *et al.* 2010; Boruah *et al.* 2016). China is the biggest producer of non-wood products in the world. Bamboo, which is widely cultivated in China and other Asian areas (Hui *et al.* 2003), is one of the largest sources of non-woods for the production of paper and paperboard in Asia (Scurlock *et al.* 2000; Vu *et al.* 2004; Wang *et al.* 2015; Zhang *et al.* 2017).

Because of environmental pollution (Cardoso *et al.* 2009) and high costs, the amount of bamboo chemical pulp production in the Chinese paper industry is limited. Only several big Chinese pulp mills use bamboo as a fiber material to produce chemical pulp, although in recent times the Chinese government has energetically propagandized to enlarge its utilization.

Making chemo-mechanical pulp from bamboo species has some advantages, as the high lignin content in bamboo fibers can be efficiently utilized. However, some technical problems must be overcome (Shen *et al.* 2010). The resistance to bleaching and the low brightness of bamboo chemo-mechanical pulps should be resolved first before it can be used as a fiber furnish in high-valued paper products. Due to its special fiber structure, bamboo chips are difficult to penetrate with chemical liquors, leading to insufficient softening in the impregnation stage, which result in poor strength properties to bamboo chemo-mechanical (CMP) pulps.

Thus far, the mechanical refining process has commonly been applied in the pulping and papermaking industry to produce high-yield pulps, such as TMP (thermomechanical pulp), CTMP (chemo-thermomechanical pulp), and APMP (alkali peroxide mechanical pulp) (Mohini *et al.* 2002). In the production of the mechanical pulps, a physical treatment is used prior to the refining process to screw and tear the chips, which is favorable for chemical impregnation (Tang and Liu 2004; Xie *et al.* 2010), resulting in the improvement of brightness and strength properties, as well as reducing the energy consumption.

The objective of the current study is to compare two kinds of extruding devices, the lower-cost twin-screw extruder (TSE) and the higher-cost model screw device (MSD), to improve the brightness of bamboo CMP, and to reduce production costs. The two kinds of extruder devices were used before chemical impregnation, and this was followed by the CMP process. Lastly, the brightness and strength properties of bleached bamboo CMP pulp were investigated.

EXPERIMENTAL

Materials

Bamboo chips of sizes 20 mm to 40 mm in length and 10 mm to 20 mm in width were provided from Qionglai country, located southwest of Chengdu in the Sichuan province, China. The chips were transported to Nanjing laboratory, then sealed in plastic woven bags and kept at 2 °C to 5 °C for three years, after which most of the chips had become moldy. The chips were screened in a TMI chip classifier (Universal Engineering Corporation, Uttar Pradesh, India) to remove fines and oversized pieces. Representative chips were first ground into power and then screened using sieves. Finally, the powder with particles sized between 250 µm and 425 µm was air-dried for 24 h in preparation for chemical content analysis. After drying, the contents of holocellulose, lignin, and pentose in the material were tested. The content of holocellulose was determined by the sodium chlorite method according to the standard GB/T 2677.10-95 (1995). The content of lignin was determined by the standard GB/T 2677.8-94 (1994). The content of pentose was determined by the standard GB/T 2677.9-94 (1994).

The dimensional characteristics of the material fibers were determined according to Franklin's method (Wang 1999). The fiber length, width, fines content, curl index, and kink index of bamboo fibers, before and after the extruding, were analyzed using a fiber quality analyzer (FQA, OpTest Equipment Inc., Hawkesbury, Canada). The pulp freeness was measured using a Canadian standard freeness (CSF) tester according to TAPPI T 227 om-99 (1999).

Methods

Absorbency

20 L H_2O at 20 °C was poured into 1000 g of extruded material. After it had been well stirred, the mixture was allowed to stand for 30 min. The free water was filtered with a 150-µm standard sieve for 30 min. Then the wet material was weighed (w). The liquid capacity (*A*) was calculated according to Eq. 1,

$$\text{A (g/g)} = \frac{\text{w} - 1000 \times x}{1000 \times x} \tag{1}$$

where *w* is the wet extruded material (g) and *x* is the dryness (%) of extruded material.

Specific energy consumption

The specific energy consumption (kwh) was computed according to Eq. 2,

$$\text{SEC (kwh/t)} = \frac{\text{TEC - IEC}}{OD} \tag{2}$$

where TEC is the total energy consumption (kwh), IEC is the idle energy consumption (kwh), and *OD* is the oven dry pulp in refining stage (t).

CMP pulping conditions

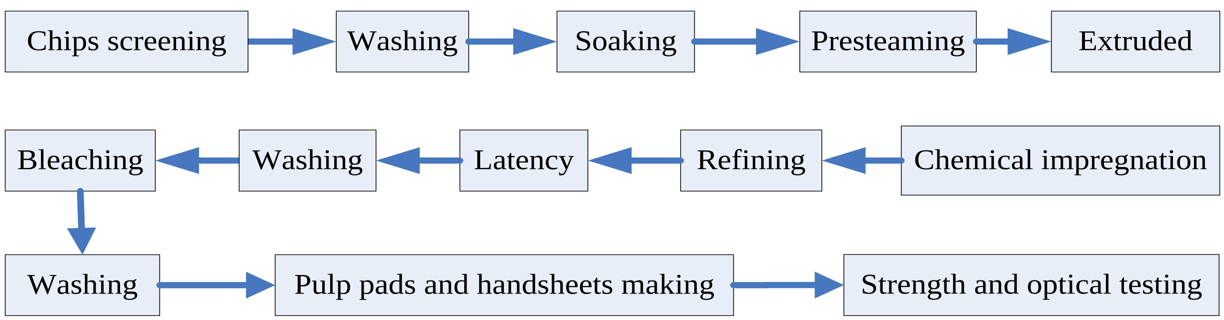

Fig. 1. The experimental flowchart

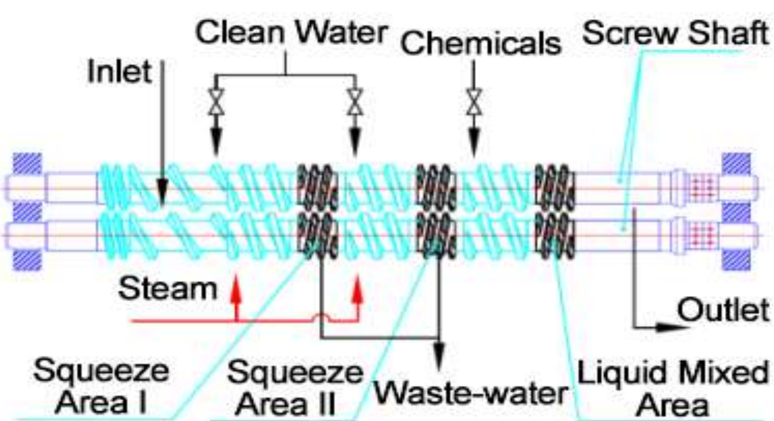

Fig. 2. Structural drawing of twin screw extruder

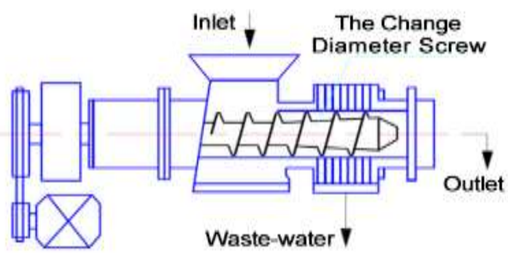

Fig. 3. Structural drawing of model screw device

The bamboo chips, after being screened and washed, were soaked in water at room temperature overnight. After filtering, the chips were steamed at the atmospheric pressure of 105 °C for 15 min, then extruded bamboo chips (at 100 °C) using a twin-screw extruder (Jiangsu Jinwo Machinery Co., Ltd., Zhenjiang, China) and a modular screw device (Andritz, Graz, Austria), respectively. After being filtered through a 7-mm sieve, the extruded chips were mixed with 2.5% sodium sulfite, 0.4% diethylenetriaminepentaacetic acid (DTPA) and 75% water, and heated at 130 °C for 10 min. The pretreated bamboo chips were refined using a Kumagai Riki Kogyo refiner (KRK No. 2500-II, Kumagai Riki Kogyo Co., Ltd., Tokyo, Japan) under an atmospheric pressure, targeted at a given Canadian Standard Freeness (CSF) of 100 to 600 mL CSF. After refining, the pulp samples were washed by water and kept in a cool room at 4 °C prior to bleaching and testing. The experimental diagram is shown in Fig. 1, and the structures of the two devices (the TSE and MSD) are shown in Figs. 2 and 3.

Bleaching

The pulps were placed into a poly-plastic bag and preheated in a temperature-controlled water bath, then mixed manually with bleaching liquor, sealed, and placed back into the temperature-controlled water bath. After each bleaching, the bleaching filtrate was de-watered from the wet pulps, and some of it was taken for measurement of the residual chemicals and pH value. The pulps were acidified to pH 5 with sulfuric acid and then washed with distilled water. The clean pulps were kept for brightness testing and further testing. Hydrogen peroxide bleaching for alkali optimization was conducted at 90 °C, 120 min, 10% consistency, 2% sodium silicate (Na_2SiO_3), and 0.1% DTPA.

Pulp properties

A set of paper-sheets (60 g/m^2) were made from each pulp sample according to TAPPI T205 sp-95 (1995) and kept overnight in a conditioning room in accordance with TAPPI T402 sp-98 (1998). The light scattering coefficient and the brightness of the paper-sheets were tested according to TAPPI T425 om-96 (1996) and TAPPI T452 om-98 (1998), respectively, using a color and whiteness testing machine (Wenzhou Baien Instrument Co., Ltd., Wenzhou, China). The tensile and burs strengths were measured according to TAPPI T494 om-96 (1996) and TAPPI T403 om-97 (1997), respectively, using TLS testing machines (Techlab Systems S.L., Lezo, Spain). The tear strength of the papers was measured according to TAPPI T414 om-98 (1998), using a Messmer tester (Messmer Instruments Ltd., Ronkonkoma, NY, USA). The thickness of paper-sheets was measured according to TAPPI T411 om-97 (1997) using a thickness tester (Hangzhou Qingtong and Boke Automation Techno Technology Co., Ltd., Hangzhou, China).

RESULTS AND DISCUSSION

Raw Material Characterization

The extruder devices (MSD and TSE) pre-conditioned the bamboo material by compressing and working or kneading the chips. This treatment process results in high levels of compressed and de-structured chips. The process induces high levels of separation zones in the chip structure and increases fiber flexibility. The compression action squeezes out water as well as water-soluble constituents (pitch). In addition to the compression the mechanical stress causes an increased surface area of the chips.

The MSD has a tapered intermediate shaft and the helical blade with variable pitch, and it squeezes chips due to the change of space. The TSE is a co-rotating and intermeshing twin screw extruder that has two more squeeze areas than the MSD. In the MSD, the raw material was squeezed at a compression ratio of 1:4, and after treatment the moisture content of material was approximately 30%. In the TSE, the raw material was squeezed at a compression ratio of 1:3.4 and 1:2 in different squeeze area respectively, and the moisture content of the treated material was approximately 50%

The effect of the extrusion on the material is shown in Fig. 4. After MSD extrusion, the shape structure was torn and twisted, but the macro size was not changed, because the material received little shear force. The material absorbency was 1.32 g/g. After TSE treatment, the shape structure was completely destroyed, while the macro-size was considerably smaller. The absorbency was 4.50 g/g, which was three times greater than that extruded by the MSD. The higher absorbency was able to improve the swelling capability of the fiber and thus improve the brightness and physical performance of handsheets.

Fig. 4. Outward appearance of raw material and extruded materials

The effect of the extrusion on the material is shown in Fig. 4. After MSD extrusion, the shape structure was torn and twisted, but the macro size was not changed, because the material received little shear force. The material absorbency was 1.32 g/g. After TSE treatment, the shape structure was completely destroyed, while the macro-size was considerably smaller. The absorbency was 4.50 g/g, which was three times greater than that extruded by the MSD. The higher absorbency led to an improvement of the swelling capability of the fiber; enhanced absorbency could be attributed to osmotic forces and the chemical reaction ability of the liquid (Rezai and Warner 1997).

The chemical compositions of the bamboo chips and extruded chips are listed in Table 1. The lignin contents of the raw materials of the bamboo from the present study were in agreement with those reported by Okan *et al.* (2013), and the holocellulose contents were a little more than those reported by Okan *et al.* (2013). Evidently, the holocellulose content of the bamboo chips was somewhat lower than that of eucalyptus, massoniana, and canola straw, but similar to that of wheat straw. The pentose content in the bamboo material was nearly twice that of the eucalyptus and massoniana, as listed in Table 1, but lower than that of wheat straw, as reported by Zhao *et al.* (2013). Moreover, neither of the two extruding methods had a noticeable effect on the chemical composition of the materials.

Table 1. Chemical Composition of Bamboo and Other Cited Materials

	Reference	Accepted Size[b] (wt.%)	Holocellulose (wt.%)	Lignin (wt.%)	Pentose (wt.%)
Raw materials	PS*	n.d.	72.94	23.98	21.01
Extruded by TSE	PS*	62.52	71.27	25.77	22.37
Extruded by MSD	PS*	79.78	73.55	25.10	22.38
Bamboo	Okan *et al.* (2013)	n.d.	70.5	24.5	n.d.
Eucalyptus	Yang (2001)	n.d.	77.80	27.45	10.27
Massoniana	Zhou *et al.* (2000)	n.d.	77.50	27.44	13.37
Canola straw	Hosseinpour *et al.* (2010)	n.d.	77.5	20.00	17.00
Wheat straw	Zhao *et al.* (2013)	n.d.	70.41	14.33	25.02

* Present study; Accepted size: above 7 mm holes sieve; n.d.: not detected

The fiber morphology of bamboo chips and extruded chip fibers are listed in Table 2. As shown, the fiber length of the raw material is half of that reported in the literature by Yang and Chen (2002), possibly because of the role of microorganisms. The length of the chips extruded by MSD was greater than that extruded by TSE, but less than that of the raw material. The widths of the raw material and extruded chips were nearly the same, though slightly wider than that reported in the literature by Yang and Chen (2002). The results in Table 2 further show that the fiber length was decreased, while the fines content and kink index were increased during the extruded stage for both the extruding force and shearing force. The fiber length, width, kink index, and curl index of chips extruded by TSE were decreased compared with those extruded by MSD, while the fines content increased nearly 67.4%. Hong Chuanzhen (Hong *et al.* 1997) had reported that during the initial beating-up period, with the decrease of kink index and curl index, the strength properties (tensile index, burst index, and tear index) of the paper-sheets would be increased.

Table 2. Fiber Morphology of Bamboo Raw Material and Extruded Material

Sample	AL (mm)			AW (um)	L/W	Fines (%)		KI (1/mm)	CI
	A	LW	WW	A	A	A	LW	A	LW
Raw Materials	0.998	1.513	2.035	18.0	55.4	19.19	2.79	3.09	0.297
TSE	0.641	0.930	1.273	18.4	34.8	24.99	6.16	3.27	0.243
MSD	0.854	1.312	1.776	19.0	44.9	20.20	3.68	3.43	0.296
Bamboo[d]	1.99	n.d.	n.d.	15.0	132.7	n.d.	n.d.	n.d.	n.d.

n.d.: not detected, d: Yang *et al.* 2002, AL: Average length, AW: Average width, L/W: Length/ width, KI: kink index, CI: curl index, A: Arithmetic, LW: Length weighted, WW: Weight weighted

Influence on Specific Energy Consumption

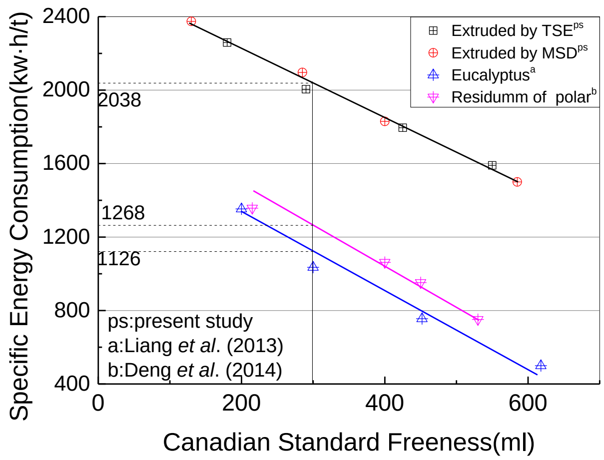

Fig. 5. Comparison of specific energy consumption of refining stage

Specific energy consumption (Zhang *et al*. 2016) is defined as the motor load divided by the production rate (oven dry wood), and it is adjusted by regulating the refiner plate gap clearance and dilution water flow rates. Refining intensity, defined as the specific energy applied to a unit mass of fiber per refiner bar impact, is a function of cumulative forces applied to the fiber during its residence time in the refiner (Sain et al. 2002); it is related to raw material characteristics and chip impregnation. Deng *et al.* (2010) had reported that specific energy consumption decreased with the increase of the amount of chemicals in the impregnation stage. Specific energy consumption (Fig. 6) of bamboo pulps is nearly the same in the refining stage when treated with TSE and MSD, respectively, as in the extruding stage, respectively. However, it is much higher than that of eucalyptus pulps (Liang *et al*. 2013) and residuum of polar pulps (Deng *et al*. 2014), perhaps because wood chips have better uniformity than bamboo; and because bamboo has hard skin and joints which would consume much more energy.

Influence of Bleaching Efficiency by Different Extruding Methods

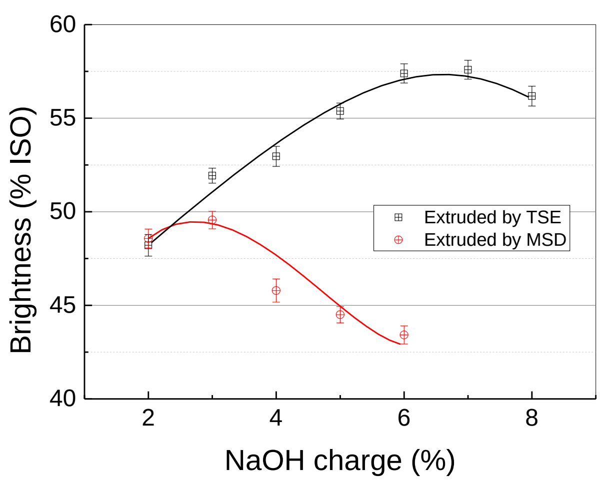

Fig. 6. Comparison of brightness bleached at 12% H_2O_2 from different extruded devices

The NaOH and H_2O_2 are two important components of the hydrogen peroxide bleaching of mechanical pulps (Shen *et al.* 2006). To investigate the bleaching ability of bamboo CMP from different extruded devices, alkali optimization was conducted at the usage level of 12% H_2O_2 (Fig. 6). The results found were the same as those found in the literature, where at a given hydrogen peroxide application level, there was a peak for the brightness of the bleached pulps that indicated the optimal alkali dosage for bleaching at the given hydrogen peroxide level. The optimized alkali dosages were different at the same level of H_2O_2 usage for the two extruded devices. At the same level of 12% H_2O_2, the brightness of the pulps extruded by MSD was approximately 49.6% ISO with optimized 3% NaOH, while that of the pulps extruded by TSE reached approximately 57.6% ISO with optimized 6% NaOH. It was clear that at the same level of 12% H_2O_2, the pulps extruded by TSE could achieve higher brightness than those extruded by MSD, which had 8% ISO brightness.

Effect of Physical Properties and Optical Properties of Paper-sheets Processed by Different Extruding Methods

To compare the physical properties of the bleached pulps from the different extruded devices, the following bleaching conditions were used according to the previous research results: 12% H_2O_2, 3% to 6% NaOH. The other conditions used in bleaching were: 0.1% DTPA, 2% Na_2SiO_3, temperature 90 °C, 120 min.

Table 3. Physical Properties and Optical Properties of Paper-sheets

	Extruded by TSE			Extruded by MSD		
	Before Bleaching	After Bleaching		Before Bleaching	After Bleaching	
NaOH (%)	n. d.	3	6	n. d.	3	6
CSF (mL)	425	375	340	400	360	340
Brightness (%ISO)	--	49.6	43.8	--	48.7	57.6
Bulk ($cm^3 \cdot g^{-1}$)	3.89	3.73	3.00	3.85	3.61	3.12
Tensile Index ($mN.m^2 \cdot g^{-1}$)	6.30	9.02	15.11	6.12	8.76	13.97
Burst Index ($kPa \cdot m^2 \cdot g^{-1}$)	0.32	0.42	0.75	0.34	0.51	0.77
Tear Index ($mN \cdot m^2 \cdot g^{-1}$)	1.25	1.70	2.69	1.46	1.97	2.67
Opacity (%)	98.39	92.5	94.02	97.86	92.65	89.07
Light Scattering Coefficient ($m^2 \cdot kg^{-1}$)	33.42	39.23	34.93	32.78	37.56	36.41
Absorption	10.88	2.59	4.43	9.71	3.04	1.91

n. d.- not detected

The strength properties of the unbleached and bleached pulps from different extruding methods are shown in Table 3. It can be seen that before bleaching, the strength properties of the pulps from different extruding methods were nearly same. After bleaching, the strength properties (tensile index, burst index, and tear index) of the bleached pulps increased on different scales compared with those of the unbleached pulps, which was consistent with previous research results (Shen *et al.* 2009). Moreover, with the increasing usage of NaOH, the strength properties also increased on different scales. At the same usage of 3% NaOH, bleached TSE-CMP had a higher tensile index than bleached MSD-CMP, while it had a lower tear index and burst index. When the NaOH usage increased to

6%, the bleached TSE-CMP had nearly the same bulk burst index and tear index as the bleached MSD-CMP, while the former also had a higher tensile index than the latter, which conformed to the previous results.

The optical properties of paper-sheets made from the bamboo chips using different extruding methods are listed in Table 3. It could be seen that the light scattering coefficient of bleached CMP varied between 34.93 m^2/kg and 39.23 m^2/kg, while the brightness varied between 43.8% ISO and 57.6% ISO. As also seen in Table 3, the light scattering coefficient decreased with the increase in the dosage of the NaOH in the bleaching process. Moreover, the bleached TSE-CMP paper-sheets had higher light scattering coefficients than did the bleached MSD-CMP paper-sheets when bleached with 3% NaOH, while the bleached TSE-CMP paper-sheets had a lower light scattering coefficient than the bleached MSD-CMP paper-sheets when bleached with 6% NaOH, which was in agreement with Seth (1990) and Fatehi *et al.* (2009b). Although an increase in the fines content of the pulps could increase the light scattering coefficient of paper-sheets, the improvement in fiber bonding (and thus increase in contact area of fibers) led to a decrease in the light scattering coefficient (Seth 1990; Fatehi *et al.* 2009b).

CONCLUSIONS

1. The compositions of bamboo materials extruded by TSE and MSD were generally the same. Compared with MSD, the bamboo materials extruded by TSE were characterized by shorter fibers, higher fines contents, and lower kink and curl indices.
2. The absorbency of the TSE extruded materials (4.50 g/g) was three times that of the materials extruded by MSD.
3. When bleached at the usage level of 12% H_2O_2, CMP-TSE could achieve higher brightness than CMP-MSD, with a brightness increase of 8% ISO. At the same time, the tensile index improved while other strength properties remained nearly same.
4. The twin-screw extruder, as a low-cost extruder device, could be used instead of the common higher-cost model screw devices.

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