The physical and chemical properties of hemp fiber prepared by alkaline pectinase–xylanase system

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Abstract Degumming is the vital and critical step in the preparation of hemp fiber for textile application. However, the traditional chemical degumming processes use large amounts of harmful chemicals, especially strong alkalis, which have caused severe challenges to the environment. The reaction conditions of alkaline pectinase and alkaline pectinase were studied in this research, and the alkaline pectinase-xylanase system was successfully applied to the degumming of hemp fibers in mild conditions (T = 55 °C and pH = 8.0) without strong alkali. A comparative analysis of hemp fibers treated under different conditions showed that the alkaline pectinase-xylanase system degummed up to about 50% gum removal within 5.5 h, making the fibers smoother and stronger. After alkaline pectinase-xylanase system treatment (0.6 g pectinase, 0.3 g xylanase, 55 °C, pH 8.0, 5.5 h), the removal ratio of pectin and hemicellulose reached 75% and 40%, respectively. And linear density and tenacity of the fiber were 17.4 dtex and 5.62 cN/dtex, respectively. SEM, FT-IR and XRD analysis furthermore demonstrated the excellent effects of the proposed process. The degumming fiber had better water retention performance (513%) and moisture sorption (8.9%), which has more excellent application prospects in the textile industry. Moreover, the method abandons the use of acid and alkali and can provide an eco-friendly degumming process for hemp fiber.
Introduction

Nowadays, serious environmental issues have attracted increasing global attention, such as water pollution, energy consumption. Approximately 22% of global yearly freshwater was consumed by the manufacturing industries, which produces large amounts of wastewater (Islam et al. 2019). In the manufacturing industries, the textile industry is considered one of the most severe environmental pollution industries due to the extensive use of hazardous chemicals and high consumption of water and energy, especially in the bast fibers textile industries (Chen et al. 2021; Jena et al. 2015; Zimniewska 2022). Therefore, green degumming technology is an important strategy to promote the sustainability of the bast textile industry.

Hemp, which originated from central Asia, is most likely the oldest cultivated fiber plant. Scientists have utilized advanced technologies to cultivate non-toxic or low-toxic hemp, which has been planted on a large scale in many places, such as China, France and the United States (Ranalli et al. 2004; Schäfer et al. 2006). Furthermore, as a recyclable textile fiber resource, hemp has many excellent characteristics, such as good tensile strength, high moisture absorption and quick-drying, excellent antibacterial properties and potential sustainability and biodegradability, which make hemp fiber have huge application potential in the textile industry, and meanwhile, it is irreplaceable among natural fibers (Liu et al. 2019; Milanovic et al. 2012; Wang et al. 2003). However, raw hemp contains a large amount of non-cellulose compositions, such as pectin, lignin, and hemicellulose, which make hemp fiber coarse and weak, limiting the development and application in high-value textile and composite materials (Kozlowski et al. 2006; Zhang et al. 2013b; Zheng et al. 1988). Degumming is the dominant step in preparing hemp fiber for textile application (Jinqiu et al. 2010; Lyu et al. 2022), but certain non-cellulose materials should be retained to make hemp fiber suitable for further spinning (Liu et al. 2019). However, the traditional chemical degumming with strong acid and hazardous alkali required high energy input and produced serious environmental pollution (Meng et al. 2019). In addition, the effect of the organic degumming process was approximate to that of chemical degumming. However, the organic degumming process still required high temperature, high reagent cost, high energy consumption, and subsequent solvent recovery was a new problem (Qu et al. 2020a; Qu et al. 2020b; Qu et al. 2020c). Therefore, it is urgent and essential to call for the development of clean, eco-friendly, effective, water and energy conservation degumming or pre-treatment processes for hemp fibers.

Alternatively, enzyme degumming methods have received widespread attention because enzymes can effectively degrade substrates and reduce pollution (Yeping et al. 2019a). At present, there are

Keywords Hemp fiber · Degumming · Alkaline xylanase · Alkaline pectinase
many studies on the use of a combination of multiple enzymes or biochemical processes for raw hemp degumming. Fang et al. (Fang et al. 2017) utilized pectinase to pre-treat raw hemp, used strong alkali for chemical degumming, and finally bleached the fiber. Although the consumption of strong alkali chemicals was reduced, the process was too long and complex. The main reason for the unstable effect of enzyme degumming was that the entanglement of the non-cellulose composition prevented enzymes from approaching the active site, thereby reducing the degumming effect (Mohanty et al. 2000; Mwai-kambo et al. 2002). Xiang et al. (Yeping et al. 2019b) used TEMPO, laccase and hemicellulase to treat raw hemp, but this paper only studied the degumming effects in acidic environments. However, there are few reports on the enzyme degumming of hemp in alkaline environments.

Pectin binds between single fiber cells and entangles with hemicellulose and lignin to form fiber bonding points, making hemp fibers into bundles of fibers in the hemp bast (Sadrmanesh et al. 2019). Pectinase can effectively hydrolyze the pectin material among the fibers, initially realize the splitting of the fiber bundles, and provide access channels for other enzymes to enter the fiber bast (Pakarinen et al. 2012; Valladares Juárez et al. 2009). As a green degumming biocatalyst, alkaline pectinase has excellent potential to replace the traditional alkaline high-temperature cooking process in the textile industry. Alkaline pectinase degumming can reduce energy consumption and alkali dosage. This process required less water and energy and produced less environmental pollution (Basu et al. 2009; Kozlowski et al. 2006). However, pectinase degumming still has low enzyme activity, long time-consuming, and unstable quality of the prepared fiber. In addition, hemicellulose is interwoven with pectin to bond the fibers together (Khalili et al. 2002), and xylan is the main component in hemicellulose (Li et al. 2021). The removal of hemicellulose is essential for the degumming process, and xylanase can effectively hydrolyze xylan to remove hemicellulose, which has a significant contribution to fiber separation. In summary, it is necessary to study the effects of alkaline pectinase and alkaline xylanase on hemp degumming.

Based on the hydrolysis effect of alkaline pectinase and alkaline xylanase in removing non-cellulose substances, this work was to provide an eco-friendly degumming process for hemp degumming. In this study, parameters such as the dosage and time of alkaline pectinase and alkaline xylanase were studied, and the synergistic effect between the two biological enzymes was analyzed. Furthermore, microstructure and surface morphology were analyzed by scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FT-IR) and X-ray diffraction (XRD). Moreover, the mechanical and moisture absorption properties of the fiber were tested to assess the fiber quality and potential use. The alkaline pectinase-xylanase system provided a green process for the preparation of hemp fiber, and this study can provide a reference for the degumming of other bast fibers.

### Experimental details

#### Materials and chemicals

Raw hemp used in this research was cultivated from Heilongjiang province, China. Alkaline xylanase (activity: 85,000 U/g) was obtained from Shandong Sukahan Biological Technology Co., Ltd (Qingdao City, Shandong province, China). Alkaline pectinase (activity: 15,000 U/g) was provided by Shandong Qingdao KDN Biological Technology Co., Ltd (Qingdao City, Shandong province, China). Sodium hydroxide (NaOH), ammonium oxalate ((NH$_4$)$_2$C$_2$O$_4$), absolute ethanol (C$_2$H$_6$O), benzene (C$_6$H$_6$), sodium dihydrogen phosphate (NaH$_2$PO$_4$),

| Control groups | Different dosage of alkaline pectinase | Different dosage of alkaline xylanase | Different reaction time |
|----------------|---------------------------------------|--------------------------------------|------------------------|
| Alkaline pectinase (g) | 0.3 0.6 0.9 1.2 | 0.0 0.0 0.0 0.0 | 0.6 0.6 0.6 0.6 |
| Alkaline xylanase (g) | 0.0 0.0 0.0 0.0 | 0.1 0.3 0.5 0.7 | 0.3 0.3 0.3 0.3 |
| Reaction time (h) | 7.5 7.5 7.5 7.5 | 7.5 7.5 7.5 7.5 | 3.5 5.5 7.5 9.5 |
| Other conditions | pH = 8.0 0.2 M phosphate buffer solution, bath ratio 1:20, 55 °C |
disodium hydrogen phosphate (Na₂HPO₄) and sulfuric acid (H₂SO₄) were purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). All used chemicals obtained from commercial sources were of analytical reagent grade without further purification. And Deionized water was used as a solvent to prepare the solution.

Preparation of degummed hemp fibers

Raw hemp was dried at 50 °C in a blast oven for 24 h to obtain a constant humidity content before degumming treatments. According to the applicable work conditions of two alkaline enzymes (alkaline xylanase: T = 45–60 °C, pH = 6.5–9.0; alkaline pectinase: T = 40–55 °C, pH = 6.0–8.5), the degumming conditions were selected at a temperature of 55 °C and a pH of 8.0. The pH value of the degumming solutions was adjusted by phosphate buffer solution (0.2 M). Hemp fibers (25.0 g dry hemp) were immersed entirely into the degumming solution, and the bath ratio was 1:20. During the reactive process, the solutions were stirred for 1 min per hour. The degummed fibers were washed completely with deionized water and then dried at 106 °C in a blast oven for 3.0 h. The components of solutions were presented in Table 2.

Fourier transform infrared spectroscopy (FTIR)

FT-IR analysis was used to determine the chemical groups in the treated hemp fiber. FT-IR spectra were recorded on a Nicolet 6700 spectrometer (Thermo Fisher Scientific, Waltham, USA) with a spectral resolution of 4 cm⁻¹ and 30 scans, and the range was from 4000 to 600 cm⁻¹. The baseline should be corrected and smoothed before further analysis.

Scanning electron microscope (SEM)

The morphologies of the hemp fibers were observed under a scanning electron microscope (SEM, VEGA 3, TESCAN Ltd., Czech Republic). After stuck on the sample stage, the samples were sputtered with a thin layer of gold. SEM was operating at 10 kV, 20 °C and relative humidity (RH) of 65%.

X-ray diffraction analysis (XRD)

The XRD patterns were performed on a Rigaku diffractometer (D/MAX-2550 PC, Tokyo, Japan) equipped with Cu kα radiation at 40 kV and 300 mA. The patterns were recorded in the 2θ range of 5°–60° and a scan rate of 2° min⁻¹. The crystallinity index (CrI) was calculated from the ratio of the area of all crystalline peaks to the total area. MDI Jade software was used for separation of peaks, and pseudo-Voigt was used for peak fit.

Chemical components analysis

The chemical compositions were tested according to the Chinese standard GB/T 5889–86. All experiments of each sample were performed separately in triplicate, and the result was the average of the experimental results of three samples. The standard deviation was controlled within 3% of the average value.

Mechanical property tests

All samples were conditioned in standard atmospheric conditions 24 h before testing, and standard atmospheric condition was 20±2 °C and RH of
65 ± 3%. The breaking tenacity of fibers was tested by an XQ-1A fiber tensile tester (New Fiber Instrument, Shanghai, China). The gauge length and drawing speed were kept at 20 mm and 20 mm/s, respectively. The linear density, tenacity, and breaking elongation were tested according to Chinese standards GB/T 18147.4-2015 and GB/T 18147.5-2015. The average value was obtained by using results from 100 specimens, and the linear density was calculated according to Eq. (1):

$$D_{db} = \frac{10G}{NL}$$  \hspace{1cm} (1)

G is the mass in grams of fiber, n is the fiber numbers, and L is the cutting length (20 mm).

Determination of moisture sorption and the water retention value

Moisture sorption of hemp fibers was tested according to the standard method ASTM D 2654–76:1976. Degummed fibers were conditioned to a standard atmosphere (20 ± 2 °C, 65 ± 2% RH) for 24 h. Moisture sorption was calculated as a weight percentage of absolute dry material, and it was an average value of three parallel tests. Standard centrifuge method ASTM D 2402–78:1978 was used to determine the water retention value of cellulose fibers, and the results were the average of three parallel determinations. The centrifuge speed (CT 14RD-II, Shanghai Tianmei Science and Technology Industry Co. Ltd) was about 400 rpm/min.

Results and discussion

The dosages of alkaline pectinase, alkaline xylanase, and reaction time

Raw hemp was processed under different conditions, and appropriate experimental parameters were

![Fig. 1](image-url)  

Fig. 1 Residual gum rates and weight lose rates of fibers with different treatments: a alkaline pectinase control group: 0.3, 0.6, 0.9, 1.2 g, b alkaline xylanase control group: 0.1, 0.3, 0.5, 0.7 g, c reaction time control group: 3.5, 5.5, 7.5, 9.5 h
obtained by comprehensively analyzing the weight loss rate and the residual gum rate. The suitable amount of alkaline pectinase and alkaline xylanase was studied, respectively, and the results of control groups were shown in Fig. 1 (a) and (b). As the usage of enzymes increased, the weight loss rate increased, and the residual gum rate decreased sharply. The residual gum rates of alkaline pectinase control group (0.3 g, 0.6 g, 0.9 g and 1.2 g) were 32.62%, 30.33%, 29.45%, 29.32%, and the weight loss rate were 26.46%, 28.85%, 29.12%, 29.45%, respectively. After alkaline pectinase treatment, the residual gum rate and weight loss rate had a little obvious change. Considering the content of pectin in the raw hemp component was less than 5%, 0.6 g alkaline pectinase could achieve the removal of pectin in the raw hemp. The residual gum rates corresponding to alkaline xylanase control group (0.1 g, 0.3 g, 0.5 g, 0.7 g) were 28.35%, 26.23%, 24.86%, 21.41%, and the weight loss rates were 26.25%, 35.78%, 38.07%, 40.02%, respectively. Xylanase mainly hydrolyzed the xylan in hemicellulose to achieve the purpose of removing hemicellulose. Hemicellulose played a vital role in maintaining the length of the process fiber. Although the 0.5 g and 0.7 g alkaline xylanase treatments performed well at a low residual gum rate, the weight loss rate increased greatly, and the fiber strength was seriously reduced. The dosage of 0.3 g xylanase had a lower residual gum rate, and could keep the fiber with a good length and strength. The reaction time of 3.5 h, 5.5 h, 7.5 h, 9.5 h was further studied (Fig. 1 (c)), and the corresponding residual gum rate was 28.21%, 20.11%, 18.44%, 16.22%, and the corresponding weight loss rate was 25.24%, 36.56%, 44.74%, 47.42%, respectively. There was no obvious change in the fiber after the 3.5 h treatment, while the fibers after the 7.5 h and 9.5 h treatments had a low residual gum rate, but the length was too short. Therefore, the conditions used in this study were: temperature 55 °C, pH 8.0, time 5.5 h, alkaline pectinase 0.6 g, alkaline xylanase 0.3 g. In this study, the synergy between alkaline pectinase and alkaline xylanase was further studied.

Surface morphology of hemp fiber

SEM micrographs of hemp fibers presented a clear view of degumming capability. Figure 2 showed the SEM images of raw hemp fiber and degummed fibers under different conditions. The raw hemp fibers had a rough and coarse surface with no fiber exposed (Fig. 2(a)). As seen in Fig. 2 (b), hemp fibers treated

![Fig. 2 SEM images of hemp fiber. a raw hemp, b hemp treated with buffer solution, c hemp treated with alkaline pectinase solution, d hemp treated with alkaline xylanase solution, e hemp treated with alkaline pectinase-xylanase solution](image-url)
only with buffer solution were insufficient to eliminate non-cellulose substrates, and there was no separation between fibers. The fibers treated with alkaline pectinase (Fig. 2(c)) and alkaline xylanase (Fig. 2(d)) respectively had various degrees of gums removal. The fiber surface was smooth and longitudinal cracks could be observed, which demonstrated that alkaline pectinase and alkaline xylanase had significant effects on hemp degumming. Specially treated with alkaline pectinase-xylanase (Fig. 2(e)), the surface of the fiber became even cleaner and smoother, which implied that the two alkaline enzymes worked synergistically and removed efficiently entangled mutual entanglement between gum substrates.

The single fibers with primary wall and secondary wall are bonded into bundles by the middle lamellae

Fig. 3 Schematic diagram of raw hemp fiber structure and structural change during degumming process: a fiber bundle structure in raw hemp, b structure of fiber, c changes of fiber structure before and after degumming process

Table 3 Chemical composition in hemp fiber under different degumming methods

| Sample | Cellulose (%) | Hemicellulose (%) | Lignin (%) | Water soluble (%) | Pectin (%) | Others (%) |
|--------|---------------|-------------------|------------|-------------------|-----------|------------|
| 1#     | 62.32 ± 0.17  | 19.40 ± 0.08      | 9.09 ± 0.16| 5.11 ± 0.20       | 4.08 ± 0.18| 0.41 ± 0.11|
| 2#     | 67.16 ± 0.11  | 18.84 ± 0.16      | 8.77 ± 0.08| 3.01 ± 0.11       | 2.22 ± 0.16| 0.23 ± 0.01|
| 3#     | 69.51 ± 0.31  | 17.89 ± 0.26      | 8.57 ± 0.19| 3.02 ± 0.17       | 1.01 ± 0.06| 0.02 ± 0.01|
| 4#     | 73.41 ± 0.26  | 14.87 ± 0.16      | 7.71 ± 0.17| 2.91 ± 0.13       | 1.20 ± 0.07| 0.01 ± 0.01|
| 5#     | 79.41 ± 0.25  | 11.25 ± 0.10      | 6.00 ± 0.13| 2.67 ± 0.06       | 1.02 ± 0.11| 0.01 ± 0.01|

Fig. 4 Chemical composition in hemp fiber: 1# raw hemp, 2# hemp treated with buffer solution, 3# hemp treated with alkaline pectinase solution, 4# hemp treated with alkaline xylanase solution, 5# hemp treated with alkaline pectinase-xylanase solution
(Sadrmanesh et al. 2019; Terzopoulou et al. 2015), and finally form large bundles of hemp fibers (Fig. 3). During the degumming process, the raw hemp wrapped in gummy substances (Fig. 3 (c)) and the residual cortical tissue was first removed (Gorshkova et al. 2006; Nishiyama et al. 2002), and the large bundle fibers were split into smaller bundle fibers. With the drastic decrease of gummy substances under the action of enzymes, the bundle fiber become finally finer fibers.

Chemical composition

Hemp in the individual fiber state is unsuitable for spinning due to its low strength and short length (12–25 mm), which limited its further application (Liu et al. 2017). Researchers have proposed that part of the gum compositions should be retained to link single fiber as a technical fiber, which can get a certain length of the fiber bundle and be capable of spinning (Sadrmanesh et al. 2019). Chemical compositions of hemp fibers disposed of different treatments were presented in Table 3 and Fig. 3. Compared with raw hemp or other treated process, the hemp fiber (5#) treated with alkaline pectinase-xylanase solution had the highest cellulose value of 79.41%, indicating that it was sufficient to remove non-cellulose components. The removal rates of hemicellulose and pectin were 42% and 75%, respectively. In Table 3 and Fig. 4, it was similar that the changing trend of pectin and hemicellulose content both decreased simultaneously, which indicated that a variety of chemical processes were taking place in the degumming process.

Fig. 5 Pectinase interaction model: a pectinesterase interaction model, b polygalacturonase interaction model

Fig. 6 Typical structure of xylan in hemicellulose and xylanase interaction positions
bonds connected pectin and hemicellulose. They intertwined with each other and connected with cellulose intricately. Raw hemp (2#) was treated with the buffer solution, and the pectin had been significantly reduced, indicating that part of the pectin could be dissolved in the buffer solution. Comparison of single biological enzyme treatment (3#, 4#) and alkaline pectinase-xylanase treatment (5#), it was found that the reduction of hemicellulose and pectin had changed significantly, which further implied the synergistic effect of pectinase and xylanase. In addition, there was a significant decrease in lignin content, which may be caused by the removal of the entangled lignin during the removal process of hemicellulose and pectin.

1# raw hemp, 2# hemp treated with buffer solution, 3# hemp treated with alkaline pectinase solution, 4# hemp treated with alkaline xylanase solution, 5# hemp treated with alkaline pectinase-xylanase solution.

The content of pectin in the 3# sample changed more obviously than that in the 2# sample, which was mainly due to the action of alkaline pectinase. The pectinase used in this study mainly contains pectinesterase and polygalacturonase (Fig. 5), which can degrade pectin macromolecules specially (Gorshkova et al. 2012; Kashyap et al. 2001). The catalytic degradation of alkaline pectinase was a processive degradation (Robyt et al. 1963; Robyt et al. 1970). Alkaline pectinase can specifically degrade a class of pectin substances. This process was a dynamic process, and there will be the generation of degraded products. In addition, the main form of hemicellulose in hemp was xylan-type hemicellulose (Polizeli et al. 2005), which can be hydrolyzed and removed under several typical forms of xylanase (Fig. 6), making 4# had a lower gum content than 2# and 3# (Pakarinen et al. 2012; Zhang et al. 2013a). Moreover, the content of pectin and hemicellulose in 5# was lower than that in 3# and 4#, which is probably caused by the mutual promotion of pectinase and xylanase.

Chemical analysis (FT-IR)

To further identify the changes in the chemical composition of hemp fiber prepared by various methods, infrared spectroscopy analysis was performed to identify the distribution of the main chemical bonds. As shown in Fig. 7, the main difference in infrared spectra was between 2000–650 cm⁻¹. There was peak at 1320 cm⁻¹ (C=O stretching vibration), 1060 cm⁻¹ (C=O stretching vibration) and 896 cm⁻¹ (β-glycosidic bonds of carbohydrates) in the spectra curves of all samples, which was mainly attributed to the elemental functional groups in lignocellulosic materials (Yeping et al. 2019a). Results showed that cellulose characteristic peaks of samples existed in all samples, including 1335 cm⁻¹ (OH in-plane deformation), 1205 cm⁻¹ (O–H plane bending vibration), 1160 cm⁻¹ (C–O–C telescopic vibration), 1050 cm⁻¹
After degumming with alkaline pectinase-xylanase solution, the intensities of these peaks increased obviously, which was caused by the removal of gummy components and purified cellulose of hemp fiber. And treated fibers (2#, 3#, 4#, 5#) exhibited strong absorption intensities around 1110 cm\(^{-1}\) (O–H associative band of cellulose). Besides, the intensity of C=O stretching vibration from the esters of hemicellulose around 1732 cm\(^{-1}\) exhibited slightly weaker with the alkaline pectinase-xylanase treated than raw hemp. This was related to the rapid decrease of xylan under the conditions of alkaline xylanase hydrolysis. From the FT-IR analysis, we can safely conclude that the alkaline pectinase-xylanase degumming process had a good effect on removing gummy substances.

Crystal structure analysis (XRD)

To further identify the change of crystal structure in raw and degummed hemp fibers, an X-ray spectrum analysis was carried out. The diffraction patterns of samples were shown in different colors. As shown in Fig. 8, the main diffraction portions of hemp fibers appeared at around 14.8°, 16.6° and 22.8°, which were typical of cellulose I (French 2014; Jinqiu et al. 2010). This phenomenon demonstrated that the crystallization type remained unchanged after degumming. The peaks at around 22.8° became sharper compared with raw hemp, showing an increase in the degree of order of cellulose. This was ascribed to the removal of gum material and impurities from the hemp, resulting in high cellulose content.

The crystallinity index (CrI) of diffraction patterns were calculated by split-peak fitting (Garvey et al. 2005; Hult et al. 2003), and the results were in Table 4. The CrI values of treated fibers increased significantly compared to raw hemp (1#, 52.68%), implying a significant elimination of gum and liberation of cellulose in the amorphous region. The CrI of 5# under alkaline pectinase and xylanase system was 72.07%, which was significantly higher than that of single pectinase (3#, 61.73%) and single xylanase (4#, 65.34%). This may be attributed to the fact that the decomposition of pectin exposed the action site of xylan under the process of alkaline pectinase, while the action site of pectinase was also exposed under the action of xylanase. Furthermore, the two actions promoted each other to accelerate the removal of gum (Pakarinen et al. 2012), resulting more revealing of cellulose. This situation was consistent with the results of chemical composition analysis and SEM.

Physical and mechanical properties

The fineness and tenacity of the hemp fiber had a direct impact on the application range of the fiber. Figure 9 illustrated the fineness and tenacity of hemp fibers with different treatments: 2# hemp treated with buffer solution, 3# hemp treated with alkaline pectinase solution, 4# hemp treated with alkaline xylanase solution, 5# hemp treated with alkaline pectinase-xylanase solution.

### Table 4

| 2-theta at crystal plane (°) | Crystallinity index (%) | Standard deviation (%) |
|-----------------------------|-------------------------|------------------------|
| 1#                          | 52.68                   | 3.44                   |
| 2#                          | 55.86                   | 6.57                   |
| 3#                          | 61.73                   | 1.56                   |
| 4#                          | 65.34                   | 3.12                   |
| 5#                          | 72.07                   | 3.64                   |
4#) were significantly improved, and the fineness was finer. The main reason was that the action of alkaline pectinase and alkaline xylanase broke the connection between the fibers, the fiber bundles changed from large to small, and the linear density of the fibers decreased. The synergistic effect between alkaline pectinase and alkaline xylanase reduced the number of bonding points between fibers, separated the fibers from each other, and reduced the number of fibers in the bundle, resulting in a decrease in linear density. The breaking point of the hemp technology bundle fiber was not the single fiber but the bonding point between the fibers. Therefore, the strength of hemp fiber was directly related to the linear density. The greater the linear density of the fiber, the more breaking points and the lower the breaking strength of the fiber. The number of bonding points was related to the content of non-cellulose in the fiber composition: the more non-cellulose content, the more fiber bonding points and the lower the fiber strength. Under the joint action of pectinase and xylanase, the prepared fiber had the lowest non-cellulose content and the highest strength. This phenomenon was consistent with the result of chemical composition analysis and FT-IR.

Moisture sorption and water retention

Generally, water retention value is affected by fiber composition and the swelling capacity and degree of fibrillation of long fibers (Saito et al. 2004). Figure 10 depicted the water retention value of hemp fibers treated in different ways. Compared with untreated hemp fiber, the water retention value of degummed hemp fibers was slightly enhanced. The water retention value of the fiber treated with alkaline pectinase-xylanase system (5#) was about 1.7 times higher than that of raw hemp fiber, mainly due to the change of fiber surface morphology and chemical composition. After the removal of the gum substrate, the fiber structure became looser and deeper cracks appeared. There was more space among the fibers, which allowed extra water to penetrate the fibers.

In addition, there is no chemical bonding between hemicellulose and cellulose except for van der Waals forces and hydrogen bonds between cellulose and hemicellulose (Sun et al. 2003). The content of lignin could affect the swelling capacity of fiber. Lignin, which wrapped around cellulose, had a compact molecular structure that made it hard for water molecules to penetrate. The water retention value in 3# and 4# had little difference, and it demonstrated that the situation of fiber looseness played an essential role in the water retention value. Compared with raw hemp, the moisture absorption value of treated fibers had a slight change. The raw hemp fiber (1#) had the highest moisture absorption performance, mainly because it had a large amount of non-cellulose components, especially pectin and hemicellulose, and pectin and hemicellulose had abundant hydrophilic groups (Mwaikambo et al. 2002). As the content of non-cellulose in the fiber was removed, the moisture absorption of the fiber naturally decreased (Pejic et al. 2008). From the analysis, we can safely draw a conclusion that hemicellulose content was one of the main factors affecting moisture absorption performance, and this was consistent with the results of other previous studies (Milanovic et al. 2012).

Conclusion

The traditional chemical degumming processes use a lot of harmful chemicals, especially strong alkalis, which have caused serious challenges to the environment. It is urgent to call for the development of clean, water and energy conservation degumming. This research provided a greener and more eco-friendly hemp degumming process without strong alkali and
strong acid. We have found that under mild conditions (pH = 8.0, T = 55 °C), alkaline pectinase and alkaline xylanase could simultaneously exert better activity. It demonstrated that the two alkaline enzymes played a synergistic effect through degumming process, significantly removing pectin (up to 75%) and hemicellulose (up to 40%). The cellulose content of the obtained hemp fiber was about 79%, and the surface of the fiber was smooth. The results showed that the alkaline pectinase-xylanase system could effectively remove non-cellulose components and significantly improve the properties of hemp fiber. The hemp fiber treated by the alkaline pectinase-xylanase system had good water retention performance (513%), moisture sorption (8.9%) and excellent mechanical properties (17.4 dtex, 5.62 cN/dtex.). It was finer and had a lower content of gum components, which had greater application prospects in the textile industry and composite material industry. The alkaline pectinase-xylanase system provides a referable degumming solution for other bast fibers.

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Declarations

Conflict of interests The authors declare that they have no conflict of interest. This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

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