

Controlled De-Cross-Linking and Disentanglement of Feather Keratin for Fiber Preparation via a Novel Process

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ABSTRACT: Pure protein fibers were fabricated from chicken feathers via a potentially green process. In the last several decades, efforts have been made to produce keratin-based industrial products, especially fibers. However, the methods of producing keratin fibers directly from chicken feathers could not be repeated. In this research, protein fibers from chicken feathers were developed using chemicals that could be either derived from renewable resources or facilely recycled. Backbones of keratin were preserved after cleavage of disulfide bonds using cysteine. Sodium dodecyl sulfate (SDS) was applied to dissolve keratin for spinning. Increasing SDS concentration intensified the ordered conformation of keratin, first increased and then decreased the viscosity of solution, suggesting continuous disentanglement of keratin molecules and enhancement in inter- and intramolecular electrical repulsion. Diameters of the obtained fibers as small as 20 μm also proved good drawability of the keratin solution. Change in crystallinity indices was found to be consistent with that of tensile properties of the keratin fibers. In summary, regenerated fibers were successfully produced as linear keratin with preserved backbones that could be untangled and aligned in a controlled manner.

KEYWORDS: Regenerated keratin fibers, Chicken feathers, Surfactant, Controlled disentanglement, Viscosity



INTRODUCTION

Global fiber production in 2012 approached 85.8 million tons, of which approximate 50.6 million tons were synthetic fibers and about 30 million tons were cotton fibers.¹ Synthetic fibers are not sustainable because of limited petroleum reserves and rising oil price, while production of cotton, the major natural fiber, has been decreasing. Therefore, to satisfy the increasing global consumption of fibers and to resolve the problem of limited resources, it is necessary to develop fibers from alternative resources with large availability at low price.

Chicken feathers could be prospective resources to produce regenerated protein fibers. The United States poultry industry produces more than 4 billion pounds of chicken feathers each year.² Some of the feathers are autoclaved or hydrolyzed and then used as animal feed with low nutritional value,³ and the rest are disposed through landfills.

Developing regenerated keratin fibers could not only provide new sources for the fiber industry to alleviate the fiber shortage but also add value to the poultry industry and address related environmental concerns. Chicken feathers contain about 90 wt % of keratin. As small linear proteins with a few bulky side

groups and molecular weight higher than 10 kDa, feather keratin meets the molecular requirements for fiber spinning.⁴ Keratin has about 7% cysteine, which could serve as cross-linking sites to form water-stable fibers.⁵

To the best of our knowledge, no efficacious method has been developed to produce regenerated keratin fibers, although relevant research could date back several decades. In the 1940s, regenerated keratin fibers had been fabricated via wet spinning of protein–surfactant complexes in the laboratory.^{6,7} However, mechanical properties of the fibers were not reported. Nevertheless, we tried the methods and found that the results could not be repeated, and did not find any other reports regarding successful repetition of the methods as well. A recent paper reported successful electrospinning of soy protein with SDS.⁸ In the 2000s, the U.S. Department of Agriculture (USDA) launched projects to transform chicken feathers into industrial products, especially fibers. However, we did not find

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reports about related fibrous products. The latest report regarding spinning of pure regenerated keratin fibers was in 2008. Fan dissolved feather keratin in ionic liquid for wet spinning.⁹ However, the obtained fibers showed tensile strength as low as 0.2 g per denier.

Regarding composite fibers with keratin as one of the components, keratin and poly(vinyl alcohol) (PVA) composite fibers have been produced via wet spinning.¹⁰ Pure keratin fibers had advantages of sustainability and renewability compared to keratin/PVA fibers. Due to the high percentage of PVA incorporated and usage of toxic cross-linkers, the keratin/PVA fibers were nonsustainable, nonrenewable, and had limited industrial potential. In the composite fibers, PVA accounted for 33–67% of the total fiber weight. Therefore, the fibers were highly petroleum-dependent and thus were nonsustainable or nonrenewable and had potentially higher cost as the oil price increased. In addition, because 33–67% of PVA in the fibers was highly water soluble, high concentrations of formaldehyde or glutaraldehyde should be used to make the composite fibers utilizable. However, formaldehyde is increasingly restricted in the fiber industry as it arouses serious environmental and health problems.

In this research, linear keratin with preserved backbones was obtained by breaking disulfide bonds connecting the keratin networks in chicken feathers under mild conditions. Controlled disentanglement and alignment of the keratin molecules by incorporating SDS led to dissolution of water-insoluble keratin in aqueous solution with good spinnability. Effect of SDS was verified via viscosity and conformational studies. Influence of different coagulation baths on mechanical properties was also investigated. Retention of backbones during extraction and unraveling of linear keratin with SDS in spinning dopes ensured formation of pure keratin fibers with good fineness and mechanical properties. The whole process could be considered as green because the major chemicals could be produced from renewable resources and the swelling agent could be recycled.

■ EXPERIMENTAL SECTION

Materials. Chicken feather barbs were provided by Featherfiber Corporation, Nixa, MO. Sodium dodecyl sulfate (SDS, 99.0%) was purchased from Hoefer, Inc., San Francisco, CA, and urea (99.0%) was supplied by Oakwood Chemical, Inc., West Columbia, SC. Coomassie Brilliant Blue R-250 (Proteomics grade) was purchased from EMD Chemicals, Inc., Gibbstown, NJ. Chemical reagents used in SDS-PAGE analysis, including LDS sample buffer (4×), Nupage 20× MES running buffer and NuPAGE 4–12% Bis-Tris gel, were purchased from Invitrogen, Inc., Grand Island, NY. Cysteine (98.0%) was purchased from Amresco, LLC, Solon, OH. The purity of chemicals was considered in all the calculations of concentrations.

Major chemicals involved in the process were either from renewable resources or can be reused. Urea could be recycled after extraction of keratin.¹¹ Cysteine is a standard amino acid with a thiol group that shows strong reducibility. It is an environmentally benign reducing agent and can be commercially produced via fermentation.¹² SDS is synthesized by treating lauryl alcohol with sulfur trioxide gas, while the lauryl alcohol is usually derived from vegetable oils, such as coconut oil or palm oil by hydrolysis.¹³

Controlled Cleavage of Disulfide Cross-Links in Feathers. Critical conditions, such as concentration of cysteine, pH, and extraction time were used to study treatment conditions based on yield and molecular weight. The weight ratio of 8 M urea solution to chicken feathers of 17:1 was used to completely immerse chicken feathers, and the treatment temperature was 70 °C. To study the effect of reductant, cysteine concentrations of 1%, 5%, 10%, and 20% based on the weight of chicken feathers were selected. The pH was 10.5, and

treatment time was 24 h. The pH of feather dispersion was adjusted using 50% NaOH solution. Different periods of treatment time, 3, 6, 12, and 24 h, were selected, while the cysteine concentration was 10 wt % and pH was 10.5. To study the pH effect, four sets of pH, 6, 9, 10.5, and 11.5, were used, while the cysteine concentration was 10 wt % and the treatment time was 12 h. After optimization based on yield and molecular weight distribution, conditions of 10 wt % of cysteine, 12 h, and pH 10.5 were used for extraction of keratin for study on spinning dope and wet spinning.

After treatment, dispersion of feathers in 8 M urea was centrifuged at 10000 rpm for 20 min to precipitate undissolved feather residues. The supernatant was adjusted to pH 4 using hydrochloric acid and sodium sulfate to precipitate dissolved keratin. The keratin precipitate was washed three times with distilled water under centrifugation of 10,000 rpm for 20 min. The collected keratin was dried at 50 °C and pulverized.

SDS-PAGE. About 1 mg of extracted keratin from different extraction conditions was dissolved in 100 μ L of NuPAGE LDS sample buffer (1×), heated at 70 °C for 10 min, and left standing at room temperature for 2 h. The solution was vortexed prior to loading. Each sample of 10 μ L was loaded into an individual slot of the gel. After electrophoresis, the gel was stained with Coomassie Brilliant Blue R-250 for 2 h at room temperature. The gel was then destained using 10% acetic acid until a clear background was observed. The molecular weights of the protein standard mixture ranged from 3 to 188 kDa.

Viscosity. Apparent viscosity of the keratin–SDS solution was used to study the effect of SDS on expansion and disentanglement of keratin molecules. About 16.7% of extracted keratin and 5%, 7.5%, 8.75%, 9.38%, 10%, 12.5%, 15%, 17.5%, and 20% of SDS based on the weight of keratin were mixed and dissolved in a 0.3 M sodium carbonate–sodium bicarbonate buffer at pH 9.5 via heating at 90 °C for 1 h. A solution at same conditions without keratin was prepared as the control. Apparent viscosity of the keratin solution was measured using a rotary rheometer (Brookfield, model R/S Plus, Middleboro, MA) with a CC25 DIN measuring system under the mode of CSR. About 25 g of solution was used for each test. The spindle and cup were immersed in a water bath at 90 °C throughout the test. The shear rate was set at 100 s^{-1} , and the duration of each testing was 1800 s. Three specimens were tested for each condition.

Circular Dichroism (CD). Keratin was dissolved in a 0.3 M sodium carbonate–sodium bicarbonate buffer at pH 9.5 at a concentration of 16.7% with incorporation of different amounts of SDS (5, 10, 20, and 40 wt % of keratin). The solution was diluted with phosphate-buffered saline (PBS) to 0.5 $mg\ mL^{-1}$ before CD measurement to avoid strong background interference of the carbonate buffer. Each solution in a cuvette with a path length of 0.1 mm was continuously scanned over the wavelength range of 190–240 nm at a rate of 200 $nm\ min^{-1}$ on a Jasco Model J-815 spectropolarimeter (Jasco, U.K.).

Wet Spinning of Keratin Fibers. Spinning dope was prepared by dissolving 30% extracted keratin and 10% SDS (based on weight of keratin) in 0.3 M sodium carbonate–sodium bicarbonate buffer at pH 9.5. The spinning dope was allowed to age for 24 h at room temperature to enable disentanglement of polypeptides. The spinning dope was heated in water bath at 90 °C for 1 h before spinning. The fibers were then drawn manually in three types of coagulation bath, i.e., 10% sodium sulfate solution and 10% acetic acid (Na_2SO_4 /acetic acid), 10% ethanol and 10% acetic acid (ethanol/acetic acid), 10% methanol and 10% acetic acid (methanol/acetic acid). The fibers were washed in distilled water, dried under ambient conditions, heated at 150 °C for 2 h, drawn manually twice, and annealed at 120 °C for 1 h. The fibers were balanced in 21 °C and 65% relative humidity for 24 h prior to any test.

Morphological Analysis. Morphological analysis of fibers was studied using a scanning electron microscope (SEM, S3000N, Hitachi, Inc. Schaumburg, IL). Keratin fibers were sputter-coated with gold/palladium and observed at a voltage of 15 kV.

Tensile Properties. Fineness of the keratin fibers was measured in terms of denier, which is the weight of 9000 m of fibers in grams. The weight of known lengths of keratin fibers was measured to calculate

the denier of fibers. Tensile properties of fibers in terms of breaking tenacity and breaking elongation were tested using an Instron tensile testing machine (Norwood, MA) according to ASTM standard D-3822. In the test, a gauge length of 1 in. and crosshead speed of 18 mm min⁻¹ were used. For each condition, about 30 specimens were tested for each fiber sample. The wet strength of keratin fibers was determined immediately after immersing the fibers in water at room temperature for 30 min.

Crystallinity Analysis. X-ray diffraction studies were carried out on raw chicken feathers, extracted keratin powder, keratin fibers from sodium sulfate/acetic acid, methanol/acetic acid, and ethanol/acetic acid coagulation bath. The data were obtained using a Rigaku D/Max-B X-ray diffractometer with Bragg–Brentano parafocusing geometry, diffracted beam monochromator, and conventional copper target X-ray tube set ($\lambda = 1.54 \text{ \AA}$) to 40 kV and 30 mA at 26 °C. Diffraction intensities were recorded with 2θ ranging from 3° to 40° at a scan speed of 0.05° per second. The crystallinity index (C.I.), indicating the relative crystallinity degree of fibers, has been long used to characterize keratin fibers such as wool and was calculated using the following empirical eq 1¹⁴

$$\text{C.I.} = \frac{I_9 - I_{14}}{I_9} \quad (1)$$

where C.I. is the crystallinity index; I_9 is the maximum intensity of crystal lattice diffraction with 2θ at around 9°, and I_{14} is the minimum diffraction intensity with the 2θ at around 14°. In general, a higher C.I. value indicates higher crystallinity of the fiber sample.

Statistical Analysis. All the data obtained were analyzed by the one-way analysis of variance with the Scheffé test with a confidence interval of 95%. A *p* value smaller than 0.05 indicated a statistically significant difference. Standard deviations are shown by the error bars in the figures, and the data in the figures labeled with different numbers or characters indicate significant differences among them.

RESULTS AND DISCUSSION

Controlled Breakage of Disulfide Cross-Links. Dissolution process of chicken feathers using 8 M urea and reducing condition included swelling of keratin macromolecules by urea and breakage of disulfide bonds by cysteine. Difficulty in dissolving chicken feathers stemmed mainly from their high cross-linking degree, attributed to 7–10% of cysteine in keratin,⁵ and hydrophobic interactions due to approximate 40% of amino acids with hydrophobic side groups.¹⁵ In the 8 M urea solution, urea concentrated on the surface of protein, disturbed inter- and intramolecular hydrogen bonds, weakened the hydrophobic interaction between polypeptides and consequently led to exposure of more polypeptide chains of keratin to the solvent.¹⁶ Thus, the reductant could react with disulfide bonds that used to be buried inside the peptide assembly. The keratin extracted under swelling and reducing conditions in this research was water insoluble.

Figure 1 demonstrates molecular weights of keratin extracted from different conditions. From lane 1 to 4, all the keratins showed dark bands at 10 and 20 kDa. In lane 1, the dark smear between 28 and 188 kDa indicated that most of the extracted proteins originated from slightly alkaline hydrolysis, which broke the backbones in a nonspecific manner. Dull bands around 30 and 40 kDa appear in lanes 2 and 3, while none appear in lane 4, suggesting breakage of more disulfide bonds with a higher content of cysteine. From lanes 5 to 8, a gradual transition of molecular weight distribution from higher molecular weights to lower molecular weights could be attributed to intensified hydrolysis of keratin at pH 10.5 as time prolonged. The bands at 10 kDa in lanes 7 and 8 are much weaker than those in lanes 5 and 6, suggesting a low amount of extracted polypeptides or hydrolysis of polypeptides at this

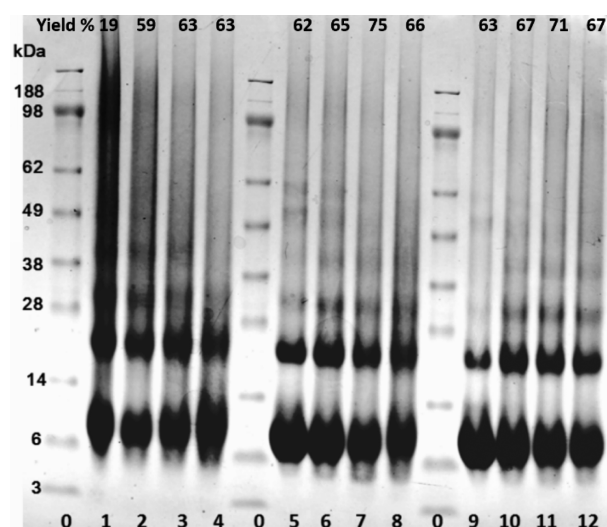


Figure 1. Effects of reductant concentration, pH, and treatment time on the percent extraction yield and molecular weight of keratin extracted from different conditions. Lane 0: standard protein markers. Lanes 1–4: 1, 5, 10, and 20 wt % of cysteine, 24 h and pH 10.5. Lanes 5–8: 3, 6, 12, and 24 h of treatment, 10 wt % cysteine and pH 10.5. Lanes 9–12: pH 6, 9, 10.5 and 11.5, 10 wt % cysteine and 12 h. Chicken feathers were immersed in an 8 M urea solution at a liquor ratio of 17:1 and treated at 70 °C.

molecular weight to water-soluble small peptides. Lane 9 represents condition with pH 6, which is much lower than the pK_a 8.2 of the thiol group in cysteine, while lanes 10, 11, and 12 represent the pH of 9, 10.5, and 11.5, respectively. In lane 9, there are strong bands at 10 kDa, while lanes 10, 11, and 12 have much stronger bands at 20 and 30 kDa. More thiolates generated at high pH can attack the disulfide bonds in feather keratins. At pH 6, undeprotonated thiol groups dominated. Cross-links in the keratin could not be completely broken, and therefore, keratin could not be dissolved.

Percent yield of extraction shown on the top of each lane in Figure 1 was also critical because the ultimate goal was to produce fibers from keratin on an industrial scale. Considering the results of yield and molecular weight, the condition of cysteine of 10 wt %, pH 10.5, and treatment time of 12 h as shown in lane 11 was selected for extraction of keratin in this study.

Effect of SDS on Conformation of Keratin. SDS played a critical role in keratin dissolution to enhance disentanglement and alignment of molecules and thus endowed the keratin solution with spinnability. Spinnability, indicating the capability of polymer solution to elongate irreversibly under stretching in one direction, could be improved if the entangled polymers were unraveled and became aligned, while a small portion of polymers were left hooked to each other.

Conformations of keratin molecules with different SDS concentrations in solution are illustrated in Figure 2. All of the spectra with strong negative absorption at 200 nm and humps at around 215–218 nm show good approximation to typical spectra of unordered conformation of polypeptides.¹⁷ The spectrum gradually weakened as SDS concentration increased from 5 to 40 wt %, indicating less random conformation of keratin molecules. At a higher concentration of SDS, keratin molecules tended to associate with more SDS and carried a stronger negative charge thereafter. The increased SDS content further dissociated the hydrophobic interaction among keratin

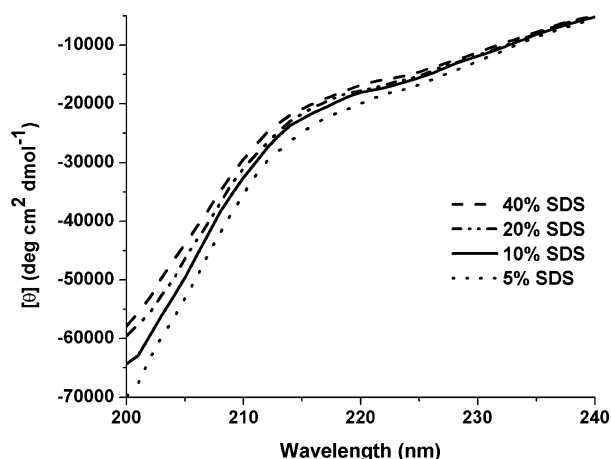


Figure 2. CD spectra of keratin dissolved in the solution with 5, 10, 20, and 40 wt % of SDS.

molecules, as well as intensified inter- and intramolecular repulsion. Consequently, the individual keratin molecules were forced to straighten, became more rigid, and assembled into more organized structures. By increasing the SDS concentration, continuous disentanglement and straightening of keratin molecules throughout the dissolution process were proved by the conformational change.

Figure 3 demonstrates that viscosity of keratin dispersion or solution increased as the concentration of SDS increased, and

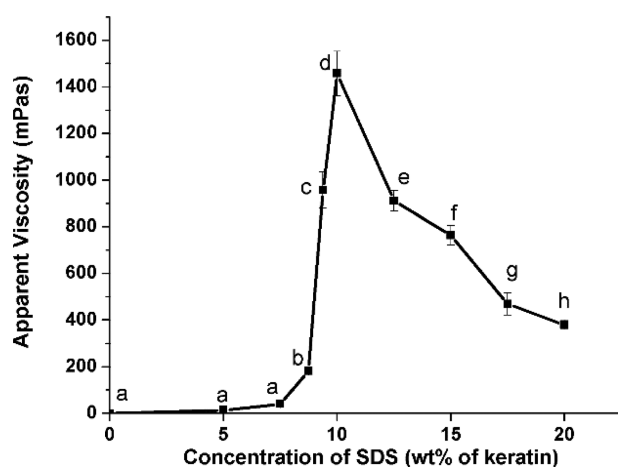
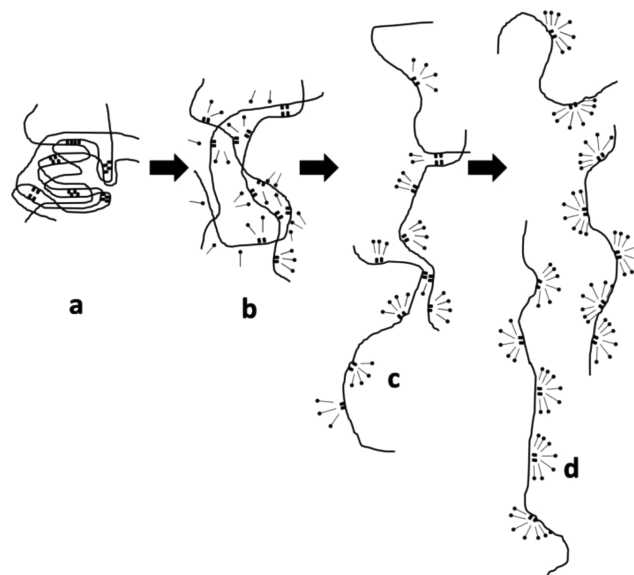


Figure 3. Influence of concentration of SDS on apparent viscosity of keratin-spinning dope.

the maximum viscosity was achieved when the SDS concentration reached 10 wt %. A further increase in SDS concentration decreased viscosity to around one-sixth of the peak value. The trend was in accordance with several reports regarding the interaction between SDS and proteins or other polymers.¹⁸

To explain the transition of viscosity shown in Figure 3, the dissociation process of keratin is proposed in Scheme 1. Without SDS in the keratin dispersion, the hydrophilic chains of keratin surrounded the hydrophobic domains in a highly coiled conformation to segregate them from water, as shown in Scheme 1a. Interaction among the coils were remarkably weak due to the limited contact area among the coils. The viscosity of less than 1 mPas was mainly attributed to interaction among water molecules. Viscosity of the dispersion increased slowly as

Scheme 1. Interaction between SDS and Keratin Molecules^a



^aSolid lines: keratin molecules. Side-by-side dots on solid line: hydrophobic domains. Bead-stick models: SDS molecules (beads, sulfate groups; sticks, C12 alkyl tails of SDS).

SDS concentration increased from 5 to 8.75 wt % as shown in Figure 3. SDS disrupted keratin coil conformations by “dissolving” hydrophobic domains and liberating hydrophilic portions in the keratin molecules. After the C12 alkyl tails of SDS associated with hydrophobic domains in keratin coils via hydrophobic interaction, the hydrophilic portions used to embed the hydrophobic domains in the coils could contact water more extensively. Therefore, the whole keratin molecules in the coils gained more surface negative charge attributed to the attached sulfate groups. As a result, the volume of coils was enlarged, and interaction among them was also strengthened, although at a relatively slow rate. Subsequently, viscosity increased steeply as SDS increased from 8.75 to 10 wt %. Here, keratin started to dissolve and became solution. Extensive liberation of keratin molecules from coils may occur, leading to a dramatic increase in contact area among keratin backbones and thus considerably strengthening the molecular interaction. At the same time, a certain degree of molecular entanglement may still exist and could also contribute to the molecular interaction, as demonstrated in Scheme 1c. However, further addition of SDS from 10 wt % rapidly decreased viscosity. It could be inferred that the remaining entanglement among keratin molecules may be completely dissociated by excess SDS, while electrical repulsion among molecules was increasingly enhanced because more SDS could join existing micelles on the surface of molecules. Breaking of entanglement and enhancement in molecular repulsion significantly weakened molecular interaction as the contact area of liberated molecules was further reduced. At this concentration, intensified interaction among SDS micelles on keratin molecules may dominate the decrease in viscosity, as illustrated in Scheme 1d.

In fiber spinning, low SDS concentration resulted in poor alignment of molecules and thus unsatisfied drawability of polymers, while high SDS concentration that led to weak interaction among molecules could result in poor physical properties of fibers. Therefore, SDS of 10 wt %, at which concentration the keratin molecules showed the strongest

interaction and appropriate disentanglement, was selected for fiber spinning.

Wet Spinning of Keratin Fibers. Figure 4 shows regenerated keratin fibers from chicken feathers on the left

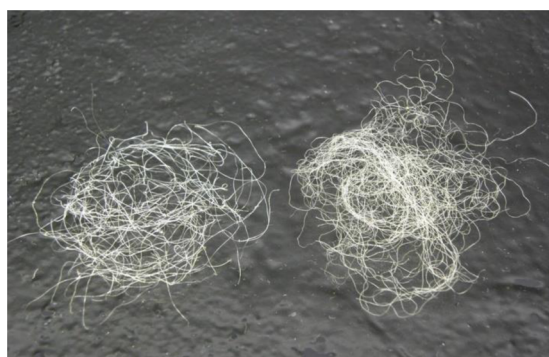


Figure 4. Digital images: (left) regenerated keratin fibers and (right) natural wool fibers.

and natural wool fibers on the right. The regenerated keratin fibers resembled natural wool fibers in terms of various sensory properties, such as length, fineness, and crimp.

Figure 5a–c illustrate morphologies of regenerated keratin fibers coagulated in solutions of sodium sulfate/acetic acid, methanol/acetic acid, and ethanol/acetic acid, respectively. All the fibers had diameters of around 20 μm , reflecting good spinnability of keratin. The fiber coagulated in sodium sulfate/acetic acid had a coarser surface than that from the alcohol-containing bath. The difference was ascribed to the relatively higher solubility of hydrophilic keratin in the aqueous electrolyte solution than in the organic solvent. Keratin molecules in the sodium sulfate solution were inclined to diffuse into the bath, and therefore, the ordered alignment of polymers in the spinning dope might be disrupted, resulting in an uneven fiber surface. However, keratin molecules with much lower solubility in alcohol tended to integrate within molecule bundles to reduce exposure of molecules to alcohol and thus better retain their ordered arrangement in the spinning dopes. Therefore, keratin fibers from the alcohol coagulation bath showed much smoother surfaces than those from the electrolyte solution.

Structure and Property Correlation in Keratin Fibers.

Mechanical properties of the regenerated keratin fibers at dry and wet states are shown in Figure 6. The dry tensile strength of the fibers coagulated in the sodium sulfate/acetic acid solution was approximate 59 MPa, which was significantly lower than 72 and 75 MPa, that of the fibers from the coagulation baths with methanol/acetic acid and ethanol/acetic acid, respectively. There was no significant difference between the strength of the fibers from the two alcohol/acetic acid solutions. All the tensile properties were remarkably lower than that of the raw feathers, which was 203 ± 74 MPa as reported.¹⁹ The wet tensile strength of fibers from the three coagulation baths of around 30 MPa was not significantly different from each other and was still much higher than that of the regenerated soyprotein fibers, which was around 19 ± 3 MPa.²⁰ The better wet strength of keratin fibers could be attributed to the remaining cross-links among the molecules. The dry elongation of the regenerated keratin fibers of about 5% and the wet elongation of about 25% were much lower than those of other regenerated protein fibers.

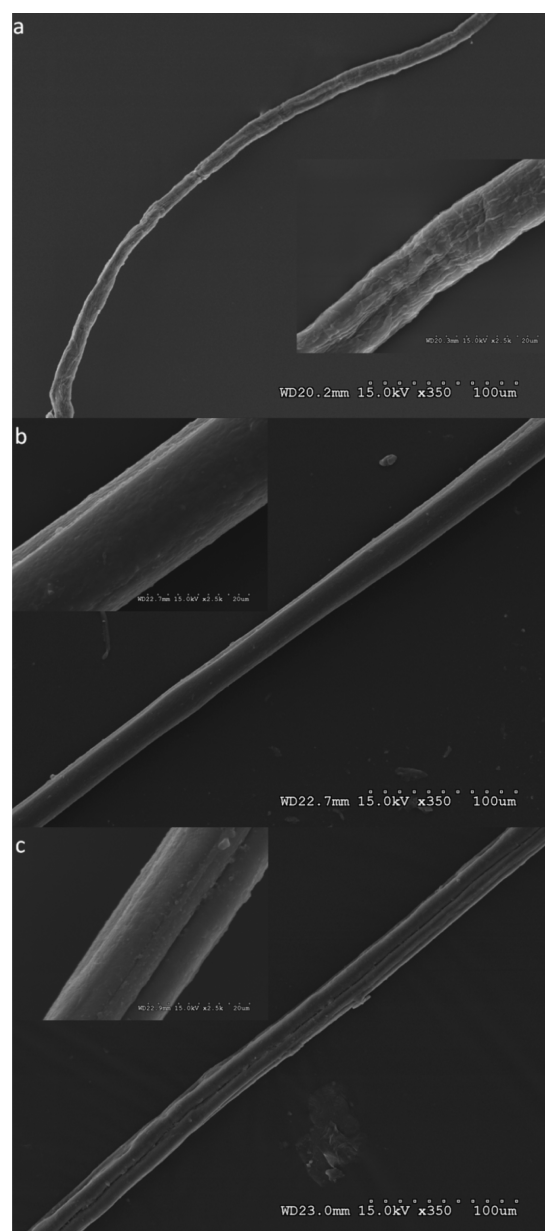


Figure 5. SEM of regenerated keratin fibers formed in (a) sodium sulfate/acetic acid coagulation bath, (b) methanol/acetic acid coagulation bath, and (c) ethanol/acetic acid coagulation bath. The magnifications are 300 \times and 2500 \times .

The coagulation baths showed critical effects on the mechanical properties of the wet-spun keratin fibers. The pH of all three coagulation baths with the same 10% acetic acid around 2.5 was lower than 5, the pI of keratin. Therefore, the effect of the acidic solidification of keratin was similar in all three conditions. SDS in the keratin solution could diffuse into the infinite coagulation bath and resulted in decreased solubility of keratin. In the sodium sulfate solution, sodium and sulfate ions interrupted hydrogen bonds between water molecules and keratin and thus disrupted the hydration layers on the keratin molecules. The hydrophobic interaction could be formed among keratin molecules and lead to solidification of keratin fibers. Regarding the alcohol coagulation bath, alcohol could induce conformational transition of protein to β -sheet,²¹ which could be beneficial to mechanical robustness of protein fibers.

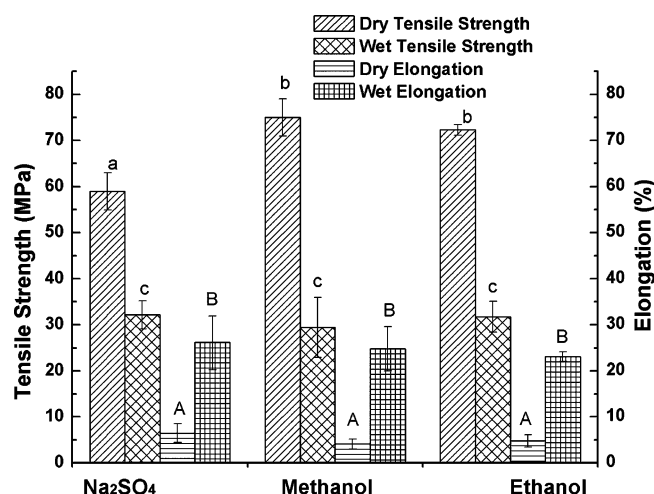


Figure 6. Effect of different coagulation baths on tensile properties, including dry tensile strength and breaking elongation and wet tensile strength and breaking elongation of regenerated keratin fibers. Different letters for each bar indicate significant differences among them.

Methanol was widely used in lab-scale wet spinning of protein fibers. The ethanol coagulation bath, which endowed regenerated keratin fibers with similar properties to methanol coagulated fibers, could have potential applications for large-scale production.

With tensile properties of about 75% for natural wool, the obtained keratin fibers have the potential to be used in industries. They could be blended with wool, cotton, or synthetic fibers to make yarns and other industrial products. Furthermore, mechanical properties of the fibers will be improved to meet the industrial standards via many widely used approaches, such as chemical cross-linking and nanoparticle filling in the future.

Figure 7 shows the wide-angle X-ray diffraction profiles of raw chicken feathers, extracted keratin powder, regenerated keratin fibers from coagulation baths of sodium sulfate/acetic acid, ethanol/acetic acid, and methanol/acetic acid, respectively. All the samples showed a typical diffraction pattern of α -keratin with a prominent 2θ peak at 20.2° and a minor peak at 9° , indicating the crystalline spacings of 4.4 and 9.8 Å, respectively. The wider peak area implied smaller crystals in the proteins. Among them, raw feathers with narrower 2θ peaks at 20.2° than the other samples should possess relatively large crystals.

After the original molecular structures were disassembled during extraction and reassembled after fiber spinning and coagulation, the minor peak of raw chicken feathers shifted from around 9.6° to 9.2° of alcohol coagulated fibers and to 9.1° of powder and electrolyte coagulated fibers. A decrease in the minor peak positions indicated increasing spacing between two adjacent lattice planes within the proteins, in other words, less compact molecular structures of the proteins.

As shown in Table 1, the decreasing trend of C.I. was also in accordance with the difference in tensile properties from raw feathers to regenerated fibers from the alcohol coagulation bath to fibers from the electrolyte coagulation bath as shown in Figure 7. The keratin powder showed an even lower C.I. value, indicating even lower crystallinity. It was suggested that the precipitated keratin in either form of powders or fibers could not completely reconstruct the tight arrangement of poly-

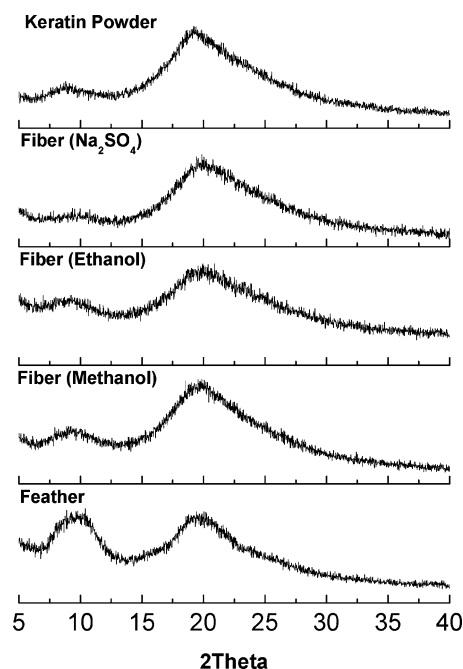


Figure 7. X-ray diffraction spectrogram of raw chicken feathers, extracted keratin powder, and keratin fibers using coagulation baths of ethanol/acetic acid, sodium sulfate/acetic acid, and methanol/acetic acid.

Table 1. C.I. of Chicken Feathers, Extracted Keratin Powder, and Regenerated Keratin Fibers Using Coagulation Baths Containing Sodium Sulfate/Acetic Acid, Ethanol/Acetic Acid, or Methanol/Acetic Acid

	feathers	methanol	ethanol	Na ₂ SO ₄	powder
C.I.	54.48	32.45	30.95	21.27	19.56

peptides existing in the raw feathers. It has been proved in the literature that aqueous organic solvent induced a decline in the α -helix and an increase in the β -sheet.²¹ With alcohol precipitation, much tighter molecular structures, probably β -sheets, could be partially rebuilt in the protein fibers and result in better mechanical performances.

CONCLUSIONS

Pure regenerated protein fibers have been successfully developed from chicken feather keratin. Keratin with preserved backbones was extracted by breaking disulfide bonds under mild conditions. SDS was incorporated to disentangle and align keratin molecules to endow them with good drawability. SDS enhanced the orderedness of keratin and first increased and later decreased the viscosity of the keratin solution. The wet-spun fibers from keratin–surfactant spinning dopes had diameters as low as 20 μm , which indicated the good spinnability of the keratin solution. The crystallinity indices of fibers from different coagulation baths changed in the same trend as the tensile properties. Cleavage of disulfide cross-links in keratin with retained backbones and dissolution of keratin using SDS was critical to regenerate protein fibers.

The dissolution methods developed in this research will have considerable broad impacts on exploring applications of many highly cross-linked proteins from biofuel and agricultural industries. For example, sorghum proteins are generated from the bioethanol industry in large quantities but with limited

applications because they are insoluble in common solvents due to the high cross-linking degrees. The dissolution method developed in this research will make the dissolution of sorghum proteins possible. It could be inferred that many available highly cross-linked proteins (e.g., sorghum proteins) as byproducts in biofuel and agricultural industries could be developed into useful industrial products, such as films, sponges, and fibers.

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Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) Rauschendorfer, L. M. *Global Development of Fiber Production*. http://www.chemistryviews.org/details/news/4723361/Global_Development_of_Fiber_Production.html (accessed June 16, 2013).
- (2) Xia, Y.; Massé, D. I.; McAllister, T. A.; Beaulieu, C.; Ungerfeld, E. Anaerobic digestion of chicken feather with swine manure or slaughterhouse sludge for biogas production. *Waste Manage.* **2012**, *32*, 404–409.
- (3) Coward-Kelly, G.; Chang, V. S.; Agbogbo, F. K.; Holtzapple, M. T. Lime treatment of keratinous materials for the generation of highly digestible animal feed: 1. Chicken feathers. *Bioresour. Technol.* **2006**, *97*, 1337–1343.
- (4) Poole, A. J.; Church, J. S.; Huson, M. G. Environmentally sustainable fibers from regenerated protein. *Biomacromolecules* **2008**, *10*, 1–8.
- (5) Arai, K. M.; Takahashi, R.; Yokote, Y.; Akahane, K. Amino-acid sequence of feather keratin from fowl. *Eur. J. Biochem.* **1983**, *132*, 501–507.
- (6) Harris, M.; Brown, A. E. Natural and synthetic protein fibers. *Text. Res. J.* **1947**, *17*, 323–330.
- (7) Evans R. L. Regenerated Keratin. U.S. Patent 2,434,688, 1948.
- (8) Xu, H.; Cai, S.; Sellers, A.; Yang, Y. Intrinsically water-stable electrospun three-dimensional ultrafine fibrous soy protein scaffolds for soft tissue engineering using adipose derived mesenchymal stem cells. *RSC Adv.* **2014**, *30*, 15451–15457.
- (9) Fan, X. Value-Added Products from Chicken Feather Fibers and Protein. Ph. D. Thesis, Auburn University, Auburn, AL, 2008.
- (10) Qian, X.; Liu, H. The optimization of regeneration feather protein /PVA composite fiber's production technology using gray clustering analysis. *Adv. Mater. Res. (Durnten-Zurich, Switz.)* **2011**, *332–334*, 500–504.
- (11) Behrendt, J.; Arevalo, E.; Gulyas, H.; Niederste-Hollenberg, J.; Niemiec, A.; Zhou, J.; Otterpohl, R. Production of value added products from separately collected urine. *Water Sci. Technol.* **2002**, *46*, 341–346.
- (12) Wada, M.; Takagi, H. Metabolic pathways and biotechnological production of L-cysteine. *Appl. Microbiol. Biotechnol.* **2006**, *73*, 48–54.
- (13) Gallezot, P. Process options for converting renewable feedstocks to bioproducts. *Green Chem.* **2007**, *9*, 295–302.
- (14) Long, J. J.; Cui, C. L.; Wang, L.; Xu, H. M.; Yu, Z. J.; Bi, X. P. Effect of treatment pressure on wool fiber in supercritical carbon dioxide fluid. *J. Clean. Prod.* **2013**, *43*, 52–58.
- (15) Frank, H. S.; Franks, F. Structural approach to the solvent power of water for hydrocarbons; Urea as a structure breaker. *J. Chem. Phys.* **1968**, *48*, 4746–4757.
- (16) Grazziotin, A.; Pimentel, F. A.; de Jong, E. V.; Brandelli, A. Nutritional improvement of feather protein by treatment with microbial keratinase. *Anim. Feed Sci. Technol.* **2006**, *126*, 135–144.
- (17) Tiffany, M. L.; Krimm, S. Effect of temperature on the circular dichroism spectra of polypeptides in the extended state. *Biopolymers* **1972**, *11*, 2309–2316.
- (18) Holmberg, C.; Sundelöf, L. O. Temperature dependence of hydrodynamic properties and surfactant–polymer interaction in solution. The EHEC/SDS/Water System. *Langmuir* **1996**, *12*, 883–889.
- (19) Zhan, M.; Wool, R. P. Mechanical properties of chicken feather fibers. *Polym. Compos.* **2011**, *32*, 937–944.
- (20) Reddy, N.; Yang, Y. Soyprotein fibers with high strength and water stability for potential medical applications. *Biotechnol. Prog.* **2009**, *25*, 1796–1802.
- (21) Tsukada, M.; Freddi, G.; Monti, P.; Bertoluzza, A.; Kasai, N. Structure and molecular conformation of tussah silk fibroin films: Effect of methanol. *J. Polym. Sci., Part B: Polym. Phys.* **1995**, *33*, 1995–2001.