



Extraction, characterization and potential applications of cellulose in corn kernels and Distillers' dried grains with solubles (DDGS)

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ABSTRACT

Cellulose with properties suitable for films and absorbents has been extracted from corn kernels and DDGS. Although DDGS is an inexpensive and abundant co-product that contains valuable components, it is currently not being used for industrial applications. DDGS contains about 9–16% cellulose by weight but the properties of cellulose in DDGS or even in corn kernels such as degree of polymerization (DP), morphology and crystallinity of cellulose have not been studied. In this study, cellulose was extracted from corn kernels and DDGS using alkali and enzymes. A minimum crude cellulose yield of 1.7% and 7.2% with cellulose content of 72% and 81% was obtained from corn kernels and DDGS, respectively. The solids obtained after extraction with cellulose contents ranging from 35% to 81% were made into films with tensile strength and elongation up to 42.5 MPa and 3.3%, respectively, using water and without any additional chemicals. The cellulose obtained holds water up to 9 times its weight and could therefore be used as an absorbent. The cellulose could also be used as paper, composites, lubricant and nutritional supplement.

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1. Introduction

The use of corn as the major source of ethanol in the United States generates considerable amounts of co-products generally called DDGS which is inexpensive, available in large quantities but with limited industrial applications. For instance, a gallon of ethanol produced from corn kernels generates about 7.4 pounds DDGS (Pimentel, 2003). About 10 million tons of DDGS was generated in the United States in 2006 but the estimated increase in ethanol production is bound to increase the amount of DDGS produced to about 20 million tons by 2012 (Severinghaus, 2006). Currently, DDGS is mainly used as animal feed but DDGS is reported to cause health problems in animals that could restrict the use of DDGS as animal feed (Wu & Munkvold, 2008). Therefore, it will be imperative to find new uses for DDGS to help reduce the cost of producing ethanol. More importantly, the components in DDGS such as oil, proteins and carbohydrates are inexpensive and available in large quantities and could be used to develop various products.

DDGS contains oil (8–11%), proteins (about 25–30%, with about 50% zein), cellulose (9–16%) and other carbohydrates

(Loy & Wright, 2003). The oil in DDGS has similar properties to the commercially available corn oil and could be used either in the food industry or as a biofuel (Xu, Reddy, & Yang, 2007). Zein, the major protein in corn, is suitable for various applications such as films, binders in paints and also for fibers (Lawton, 2002). However, zein currently sold on the market obtained from corn kernels by wet milling is expensive with selling price of about \$8–10 per pound. Obtaining oil and zein from DDGS would be more economical than from corn kernels but the normal process of extracting zein from corn kernels are not suitable for extracting zein from DDGS. In our previous research, we have shown that zein in DDGS can be extracted with high yield, low cost and with properties suitable for various applications (Xu et al., 2007). So far, only the properties and potential applications of oil and zein in DDGS have been studied but the extraction, properties and applications of the other major components in DDGS, i.e. the carbohydrates (cellulose and hemicellulose) have not been studied. It will be necessary to develop proper extraction conditions to obtain cellulose and hemicellulose from DDGS with properties suitable for various applications.

The purification and characterization of cellulose from various plants and bioresources has been extensively studied and cellulose from these sources has been purified using acids, alkalis, enzymes or a combination of these chemicals (Albaladejo & Munoz, 1953; Brendel, Iannetta, & Stewart, 2000; Casciani, 1947; Martin & Umansky, 1949; Udici, 1962). Generally, acidic method of

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cellulose purification provides cellulose with high purity but may damage the cellulose. Compared to the acidic method, purification using alkali (without oxygen) and enzymes yields cellulose with slightly low purity but causes little or no damage to the cellulose.

The possibility of using cellulose obtained from various sources to develop films and fibers has been studied (Yamashiki et al., 1992; Zhang, Ruan, & Zhou, 2001). Cellulose films or fibers are generally made by dissolving cellulose in solvents such as *N*-methyl morpholine *N*-oxide–water, liquid ammonia–ammonium thiocyanate–water, LiCl–1, 3-dimethyl-2-imidazolidinone, LiCl–*N*, *N*-dimethylacetamide and NaOH/Urea–water and then extruded or casted to form the fibers and films, respectively (Graenacher & Sallman, 1939; Hudson & Cuculo, 1980; Takaragi, Minoda, Miyamoto, Liu, & Zhang, 1999; Turbak, El-Kafrawy, Snyder, & Auerbach, 1981; Zhang et al., 2001). However, most of the solvents used to dissolve cellulose are either expensive, toxic or require high concentration of chemicals leading to difficulties in recovery and reuse of the chemicals that raises environmental and health concerns.

In this research, cellulose was extracted from DDGS and corn kernels and the properties and potential applications for the cellulose have been studied. The properties of cellulose such as the DP, morphology and crystallinity of cellulose have been determined and the potential of using the cellulose for films and absorbents have also been investigated.

2. Materials and methods

2.1. Materials

DDGS was supplied by Abengoa BioEnergy Corporation, York, NE. One normal cupriethylenediamine solution was purchased from GFS Chemicals Inc., Columbus, OH. SPIRIZYME PLUS (glucoamylase) and SHEARZYME (xylanase) were supplied by Novozymes, Franklinton, NJ. Anhydrous sodium acetate, glacial acetic acid and anhydrous ethyl alcohol were purchased from EMD with purity greater than 99.0%, 99.8% and 92%, respectively. Sodium hydroxide was purchased from EM science.

2.2. Cellulose extraction

Preliminary trials in our laboratory have shown that an acidic method of cellulose purification from scoured cotton using a method reported by Brendel et al. resulted in the decrease of the DP of cellulose to 240 ± 2 from 2892 ± 16 for the original cellulose (Brendel et al., 2000). Therefore, alkali and enzymes have been used to extract cellulose with the highest possible DP from corn kernels and DDGS instead of the acidic method. A schematic of the procedure used to extract cellulose is shown in Fig. 1. Initially, corn kernels and DDGS were powdered in a laboratory scale Wiley mill to pass through a 20 mesh dispenser. The oil in the powdered corn kernels/DDGS was extracted using anhydrous ethanol in a Soxhlet extraction apparatus until the extracted liquids were colorless. Zein was extracted from the dried oil-free corn kernels/DDGS using 70% (w/w) aqueous ethanol adjusted to pH 2.0 in the presence of sodium sulfite, 0.25% (w/w), at 78 °C for 2 h with a liquor to solid ratio of 10:1. The oil and zein-free DDGS/corn kernels were washed, centrifuged and dried at room temperature. The oil and zein-free solids now rich in cellulose and hemicellulose were treated with 5% aqueous NaOH at 90 °C for 5 h in the absence of air to remove hemicellulose. After this treatment, the solids obtained were washed with water to remove alkali. Enzymes glucoamylase and xylanase were used to treat the residue in NaAc/HAc buffer solution at pH 5.0 at 50 °C for 48 h to remove any remaining starch and hemicelluloses. The residues were again treated with 1% NaOH

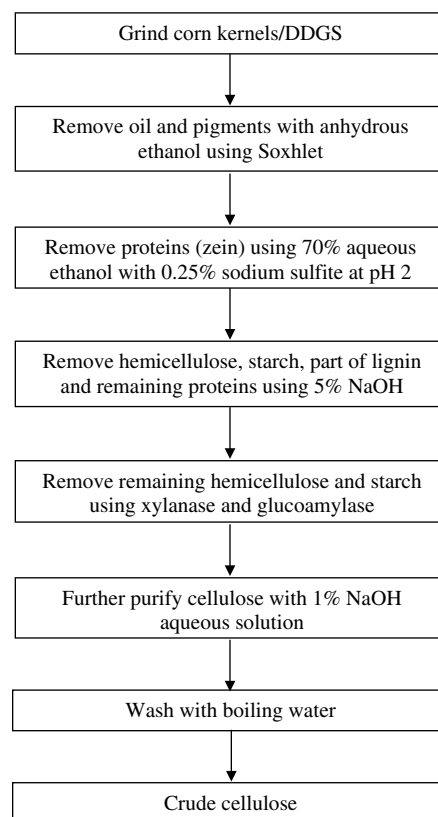


Fig. 1. Schematic of the steps used to extract cellulose from corn kernels and DDGS.

solution at 90 °C for 2 h to further purify cellulose followed by washing in boiling water. The cellulose thus obtained was dried at room temperature.

2.3. Moisture regain

The moisture regains of the cellulose from corn kernels and DDGS were determined according to ASTM standard method D 2654 under standard atmospheric conditions of at 21 °C and 65% RH.

2.4. Compositional analysis

The presence of starch in the crude cellulose from corn kernels and DDGS was determined using iodine solution. The visual change in color of starch when it comes in contact with iodine was used to assess the presence of any starch in the crude cellulose. The iodine test did not show any indication of the presence of starch in the samples after the enzyme treatment. The amount of hemicellulose and cellulose was determined in terms of the acid detergent fiber (ADF) and neutral detergent fiber (NDF). The NDF in the crude cellulose samples was measured by the method reported by Goering and Soest (1970). The ADF in the crude cellulose samples was measured according to AOAC method 973.18. Lignin in the cellulose from corn kernels and DDGS was determined as Klason lignin according to ASTM standard method D1106-96. ADF is the amount of cellulose and lignin in the samples and NDF is the amount of cellulose, hemicellulose and lignin in the samples. Therefore, the difference between the ADF and NDF gives the amount of hemicellulose. Similarly, the amount of pure cellulose in the samples was determined after subtracting the lignin from ADF. Ash in the crude samples was measured according to ASTM standard method E 1755-01.

2.5. Degree of polymerization

The average DP of cellulose from corn kernels and DDGS was calculated in terms of the intrinsic viscosity using Mark–Houwink equation (1) at 25.0 °C in 0.5 M cupriethylenediamine solution (Halidan, Nurmmamat, & Wumanjiang, 2006). The intrinsic viscosity of the cellulose was measured according to ASTM standard method D1795-96 except that the cellulose solutions were filtered with tightly woven polyester fabric and the dry weights of the impurities were measured and subtracted to obtain the weight of cellulose.

$$\eta = K (\text{DP})^{\alpha} \quad (1)$$

in which η is an intrinsic viscosity

K is a constant 1.7

α is a constant 0.8

2.6. FTIR Measurement

Infrared spectrums of the cellulose samples were recorded on a Thermo Electron Corporation FTIR (Model: Nicolet 380) in the reflectance mode. Sixty-four scans were recorded for each sample at a resolution of 32 cm⁻¹.

2.7. Morphological structure

A Hitachi S3000N model variable pressure scanning electron microscope (VP-SEM) was used to observe the morphological features of the cellulose from corn kernels and DDGS. The specimens to be observed were mounted on the conductive adhesive tape, sputter coated with gold palladium, and observed in the SEM using a voltage of 25 kV. The dimensions of the cellulose fibers were measured from the SEM images. At least 15 cellulose fibers from each sample were measured.

2.8. Physical structure

The % crystallinity of cellulose obtained from corn kernels and DDGS were determined using X-ray diffraction. Scoured cotton and cotton treated with the same extraction methods used to obtain the cellulose from DDGS/corn kernels was used for comparison and to verify if the extraction method used resulted in any damage to the cellulose. The X-ray diffraction patterns were recorded on a Rigaku diffractometer with a ½ in. divergent slit and a copper target X-ray tube set to 40 kV and 30 mA. Measurements were taken on samples that were powdered in a Wiley mill to pass through a 250 µm mesh and then pressed in a hydraulic press to form pellets. The pellets were placed in the diffractometer and the diffraction intensities were recorded for a 2θ range of 5–40°. The diffractograms obtained were analyzed individually for the % crystallinity by the multi-peak resolution method reported by Hindeleh and Johnson using the software program MICROCAL ORIGIN (Hindeleh & Johnson, 1971). The ratio of the area from the crystalline regions to the total area of the diffractogram was considered as the % crystallinity.

2.9. Obtaining crude cellulose

In addition to the cellulose obtained by the method described above, three more treatments were done to obtain crude cellulose with varying amounts of cellulose, hemicellulose and lignin to study their potential for forming films. To obtain the crude cellulose, the oil and zein-free DDGS was treated with three different concentrations of sodium hydroxide, 5%, 1% and 0.5% with a liquid to solid ratio 10:1 at 90 °C for 5 h. The crude cellulose obtained was washed and dried.

2.10. Film formation

The crude cellulose obtained was boiled in distilled water with vigorous stirring until the materials were swollen and dispersed in water to form slurry. The slurry was poured onto Teflon coated glass plates and allowed to dry under ambient conditions for the films to form.

2.11. Mechanical properties of the films

The films obtained were conditioned at 65% RH, 21 ± 1 °C for at least 24 h before testing. The breaking stress and elongation of films were measured on a MTS QTEST/10 tester according to ASTM standard method D 882-00 with an initial gauge length of 125 mm and testing speed of 25.0 mm/min.

2.12. Water retention

Water retention of the materials extracted from DDGS were measured according to ASTM standard method D2402-01 with minor modifications. The materials from DDGS were immersed in distilled water at 21 °C for overnight. The immersed materials were put into polyester fabric bags, hanged in a centrifuge tube and centrifuged at a radial acceleration of 1000g for 5 min. The solids obtained after centrifugation were weighed to determine their wet weight. The solids were later heated in an oven at 105 °C until no weight change was observed and the dry weight of the samples was noted after cooling the samples to room temperature. The ratio between the difference in the weight of the wet and dry sample and the dry weight of the sample was considered as the water retention of the sample.

2.13. Statistics

All the experiments were repeated three times unless specified. The data are reported with mean ± one standard deviation. Student *t* test was used with the level of significance being 5%.

3. Results and discussion

3.1. Cellulose yield and composition

The yield and composition of the crude cellulose from corn kernels and DDGS are given in Table 1. As seen from the table, the amount of cellulose obtained from DDGS (7.2%) was much higher than that obtained from corn kernels (1.7%) and the DP of the cellulose obtained from DDGS (2243) was also higher than the cellulose obtained from corn kernels (1693) as shown in Table 2. There is a significant difference between the cellulose DP obtained from corn kernels and DDGS with a *p* value of <0.0001. The higher DP

Table 1

The yield and composition (dry basis, db) of cellulose from corn kernels and DDGS.

	Cellulose from corn kernels	Cellulose from DDGS
Total yield (%) ^a	1.71 ± 0.05	7.24 ± 0.36
NDF (%) [#]	95.33 ± 0.42	95.04 ± 0.19
ADF (%) [#]	72.18 ± 0.40	82.10 ± 0.36
Cellulose (%) [#]	71.77 ± 0.49	80.98 ± 0.04
Hemicellulose (%) [#]	23.56 ± 0.82	12.94 ± 0.27
Ash (%) [#]	1.62 ± 0.02	1.70 ± 0.33
Lignin (%) [#]	0.41 ± 0.09	1.12 ± 0.08
Moisture regain (%) [#]	10.21 ± 0.66	8.99 ± 0.25

ADF, acid detergent fiber; NDF, neutral detergent fiber.

^a Based on corn kernel/DDGS.

[#] Based on crude cellulose.

Table 2

Characteristics of the crude cellulose from corn kernels and DDGS.

	Cellulose from corn kernels	Cellulose from DDGS
Average DP	1693 ± 48	2243 ± 46
Length of cellulose fibers (mm)	0.4–1.2	0.3–1.6
Width of cellulose fibers (μm)	12.6 ± 5.1	16.7 ± 3.3
Crystallinity (%)	43	49

of the cellulose from DDGS is probably due the chemical linkage between cellulose and lignin/hemicellulose as will be shown later in this manuscript. However, the yield of cellulose from both corn kernels and DDGS obtained in this research is lower than the cellulose content previously reported in corn kernels (3.0%) and in DDGS (10.5%) (Dong & Barbara, 1987). This is probably due to the different variety and maturity of corn kernels and the fermentation conditions used to produce DDGS. The iodine test did not show any indication of the presence of starch in the samples after the enzyme treatment.

The NDF content in the cellulose from corn kernels and DDGS are similar at about 95%. The high NDF content indicates that the cellulose obtained from corn kernels and DDGS mostly contains hemicellulose, cellulose and lignin and low amounts of other impurities. The hemicellulose content in the crude cellulose obtained from corn kernels is higher than that in the crude cellulose obtained from DDGS as shown in Table 1. The low amount of hemicellulose in the crude cellulose obtained from DDGS compared to the hemicellulose in the cellulose obtained from corn kernels should mainly be due to the easy removal of hemicellulose after fermentation to produce ethanol. It has been reported that hemicelluloses either dissolve in hot aqueous alkali solution or in hot water (Preece, 1930). Although both hot alkali and hot water were used to remove hemicellulose in this research, the persistence of hemicellulose indicates that it is probably chemically crosslinked with cellulose and/or lignin. Such crosslinking between hemicellulose, lignin and cellulose has been reported to form a stable three dimensional structure (Huber, 2006). The FTIR spectrum of cellulose from corn kernels and DDGS shown in Fig. 2 substantiates the presence of hemicellulose in the extracted cellulose. As seen from Fig. 2, the cellulose from DDGS and corn kernels have spectra similar to cotton except for additional peaks in the cellulose from corn kernels and DDGS at wavelengths of about 1750 and 2930 cm^{-1} . The similarities of the spectra especially in the finger print region (wavelengths of 1000 cm^{-1} and lower) indicate that the materials extracted from corn kernels and DDGS are

mostly cellulose. However, the additional peaks at 1750 and 2930 cm^{-1} show that the cellulose from corn kernels and DDGS has carbonyl groups and unsaturated bonds. The carbonyl groups are most likely due to the presence of hemicellulose (Lide, 2001). The peak seen at 2930 cm^{-1} in the DDGS and corn kernel cellulose is most likely due to the presence of lignin which is a large aromatic material that generates a peak at this position.

As seen from Table 1, the ash content in the crude cellulose from corn kernels and DDGS are similar at about 1.65% without any statistical difference with a p -value of 0.7089. However, the lignin contents in the crude cellulose from corn kernels are much lower than the lignin content in the cellulose obtained from DDGS. This is probably due to the higher amount of lignin in DDGS than that in corn kernels. Based on the lignin obtained from the cellulose in DDGS and corn kernels in this research, the amount of lignin in the DDGS and corn kernels translates to about 0.01% and 0.13%, respectively, much lower than 0.7–0.9% and 1.5–2.3% lignin previously reported in DDGS and corn kernels (Dong & Barbara, 1987). The much lower levels of lignin in the cellulose obtained in this research indicate that the extraction processes used in this research is capable of removing most of the lignin in the materials.

It also can be seen from Table 1 that the moisture regain of cellulose from corn kernels and the cellulose from DDGS at standard testing conditions is very similar at about 10% and 9%, respectively. However, the moisture regain of the cellulose from corn kernels and DDGS is slightly higher than that of cotton at about 8% under similar atmospheric conditions.

3.2. Morphology of cellulose in corn kernels and DDGS

The morphology of cellulose obtained from corn kernels and DDGS is shown in Fig. 3a and b, respectively. Morphologically, the cellulose from corn kernels and DDGS are similar and both the celluloses have particles and fibers. The sizes of the particles in the cellulose are not uniform and some particles may be parts of fibers that were broken during the grinding of DDGS/corn kernels before extraction and/or during extraction process. The higher magnification images of the cellulose fibers shown in Fig. 3c and d indicate that fibers from both corn kernels and DDGS are flat and ribbon like with the typical convolutions seen in raw cotton fibers. The cellulose fibers in corn kernels have length (0.4–1.2 mm) and average widths (12.6 μm) lower than those (0.3–1.6 mm and 16.7 μm) in the cellulose obtained from DDGS as given in Table 2. However, there is no significant difference between the length and width of the fibers in the cellulose obtained from corn kernels and DDGS with p values of 0.1643 and 0.1009, respectively.

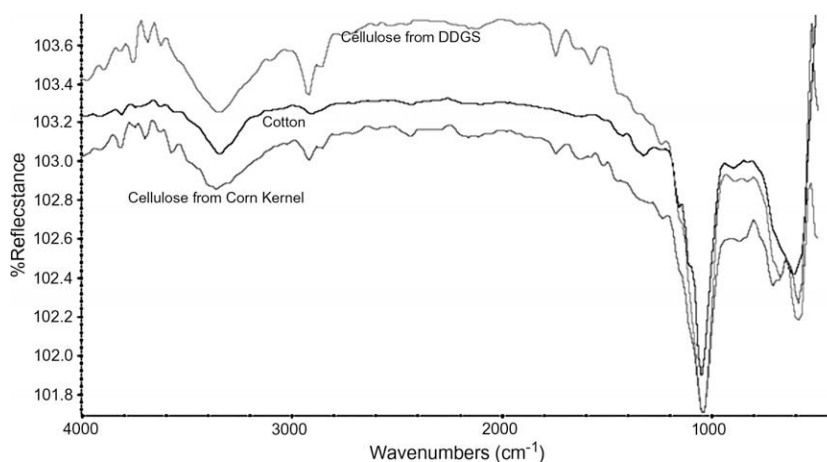


Fig. 2. FTIR spectra of cellulose from corn kernels and DDGS compared with scoured cotton measured in the reflectance mode.

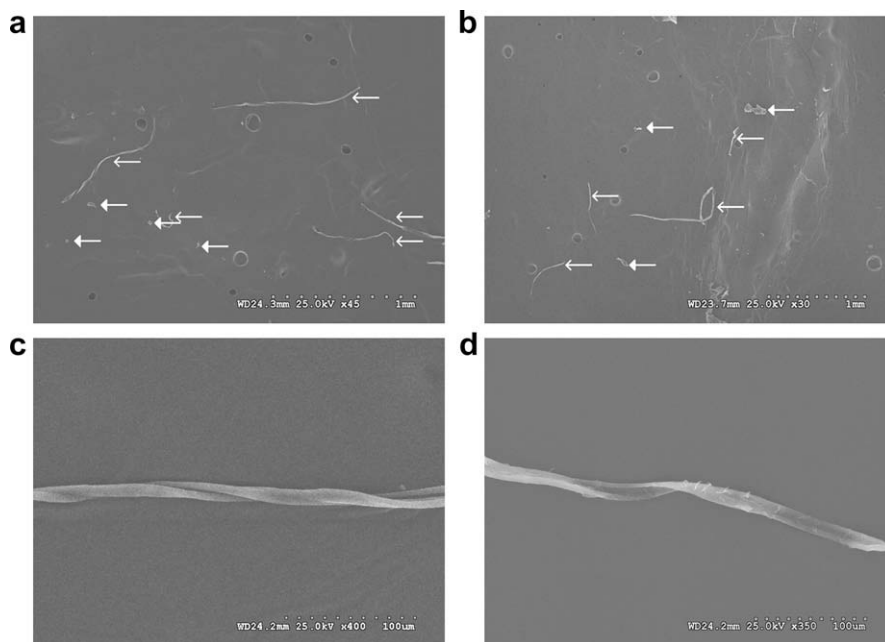


Fig. 3. (a) SEM image of crude cellulose from corn kernels, (b) SEM image of crude cellulose from DDGS, (c) SEM image of crude cellulose fiber from corn kernels and (d) SEM image of crude cellulose fiber from DDGS. Arrows with pointed heads indicate fibers and arrows with solid heads indicate particles.

3.3. Physical structure

The cellulose obtained from corn kernels and DDGS have overall % crystallinity of about 43% and 49%, lower than the % crystallinity of cotton and other common bast fibers (65–70%) as given in Table 2. The relatively low overall % crystallinity of the cellulose obtained from corn kernels and DDGS should be due to the presence of non-cellulosic impurities (Reddy & Yang, 2007). The diffractograms in Fig. 4 provide a comparison of the peak positions in the cellulose obtained from corn kernels and DDGS with cotton. As seen from the figure, the cellulose obtained from DDGS and corn kernels has the major cellulose 200 and 004 planes at 2θ angle of 22° and 35° , respectively. However, the characteristic $\bar{1}10$ and 110 peaks found in cotton (2θ between 14.9° and 16.6°) are not distinct in the cellulose obtained from DDGS or corn kernels. The two peaks have combined to form a broad peak which is reported to be due to the presence of non-cellulosic materials in the fibers (Thygesen, Oddershede, Lilholt, Thomsen, & Stahl, 2005). The similarity in the diffraction pattern between cotton and cotton treated with the same extraction processes used to obtain cellulose from DDGS and corn kernels means that the extraction processes did not alter the cellulose crystal structure.

3.4. Composition of cellulose films

Table 3 provides a comparison of the composition of films made from DDGS cellulose obtained using different extraction conditions. As seen from the table, the yield and the composition of the crude cellulose are highly dependent on the treatment conditions. There is nearly 4 times difference in yield of cellulose between the treatment conditions. Under relatively severe treatment conditions with alkali and enzymes, the yield of cellulose is low (7%) but the cellulose obtained has higher purity (81%) compared to cellulose obtained using lower concentrations of alkali. The cellulose content decreases but the hemicellulose and lignin content and the total yield of solids increases when DDGS is treated with mild alkali as seen from Table 3. This shows that the mild alkaline treatment is not able to remove the non-cel-

lulosic impurities. The moisture regains of the films increases with increases in hemicellulose content since hemicellulose can absorb higher amounts of moisture.

The presence of hemicellulose should be the major reason for the solids extracted from DDGS to form films. Since hemicelluloses that are chemically connected with cellulose swell in water, cellulose disperses homogeneously in water under vigorous stirring. When water is evaporated, hemicelluloses connect with each other and/or with cellulose with strong hydrogen bonds leading to strong films. As shown in Fig. 5, the cellulose and hemicellulose mixture obtained from DDGS easily form films but the different treatment conditions produces films with different particles. Harsher treatment conditions produce films with smaller particle size as seen in Fig. 5a and b. The most particle-free film was produced by treating DDGS with 5% NaOH/enzymes/1% NaOH as shown in Fig. 5a.

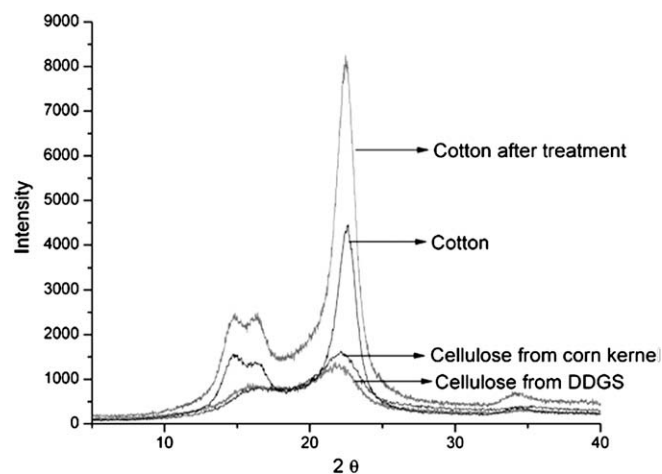


Fig. 4. Comparison of the X-ray diffraction intensities for cellulose from DDGS, cellulose from corn kernels, scoured cotton and scoured cotton treated with extraction procedure used to obtain the cellulose.

Table 3

Composition of cellulose films formed after treating oil and zein-free DDGS with various chemical concentrations for conditions.

Treatment condition	5% NaOH + enzymes + 1% NaOH	5% NaOH	1% NaOH	0.5% NaOH
Yield (db%)	7.24 ± 0.36	16.75 ± 0.35	21.38 ± 0.42	26.46 ± 1.45
Cellulose (%)	80.98 ± 0.04	53.59 ± 0.45	40.03 ± 0.28	35.09 ± 0.07
Hemicellulose (%)	12.94 ± 0.27	26.31 ± 0.95	36.67 ± 0.60	34.49 ± 1.97
Lignin (%)	1.12 ± 0.08	1.93 ± 0.26	5.74 ± 0.69	5.65 ± 0.28
Moisture (%)	8.99 ± 0.25	11.73 ± 0.12	10.58 ± 0.08	10.68 ± 0.02

Table 4

Properties of cellulose films obtained after treating oil and zein-free DDGS with various concentrations of chemicals.

	5% NaOH + enzymes + 1% NaOH	5% NaOH	1% NaOH	0.5% NaOH
Film thickness (mm)	0.078 ± 0.008	0.076 ± 0.008	0.073 ± 0.007	0.075 ± 0.013
Breaking stress (MPa)	8.24 ± 1.38	42.46 ± 5.42	28.27 ± 6.27	7.13 ± 2.23
Elongation (%)	0.86 ± 0.23	3.34 ± 0.70	1.43 ± 0.34	0.40 ± 0.13
Water retention (× dry weight)	2.67 ± 0.14	5.85 ± 0.14	8.95 ± 0.09	5.20 ± 0.01

3.5. Mechanical properties of films

The properties of the films made from the crude cellulose obtained from DDGS are given in Table 4. As seen from the table, the breaking stress of films made from the materials treated with various conditions varies from 7 to 42 MPa. Films made by treating the DDGS with 5% NaOH have the highest breaking stress and elongation. This is most likely due to the optimum level of cellulose and hemicellulose in the films. Hemicellulose acts as the binder and cellulose acts as the reinforcing material in the films. There must be sufficient amounts of hemicellulose to bind the cellulose together. In addition, the number and the size of particles in the films also influence the breaking stress and elongation of the thin films. As seen from Fig. 5c and d, films made using 1% NaOH and 0.5% NaOH treated DDGS have many large particles. The particles cause the thin films to have low breaking stress and elongation.

Both the breaking stress and elongation of films made in this research are lower than pure cellulose film or cellophane previously produced that had breaking stress in the range of 62–100 MPa and 80 MPa and breaking elongations of 3.8–14% and 8% for the cellulose and cellophane films, respectively (Zhang et al., 2001). The cellulose films previously produced were made using a 6 wt.% NaOH/4 wt.% urea aqueous solution. However, the film obtained in this research is stronger than whey protein isolate film (with 40–50% glycerol, tensile strength 3.5–8 MPa, elongation 85–127%), oleic acid zein film (tensile strength 4.2 MPa, elongation 96.3%), soy protein isolate films (with 40–50% glycerol, tensile strength 2.6–7.1 MPa, elongation 74.5%), low density polyethylene film (tensile strength 13 MPa, elongation 500%) and high density polyethylene films (tensile strength 26 MPa, elongation 300%) (Hernandez-Izquierdo & Krochta, 2008). In addition, the film obtained in this research is also stronger than commercial grocery sack (weft tensile strength 19.47 MPa, elongation 5.63% and warp tensile strength 35.97 MPa, and elongation 2.16%) tested in our lab. Using water to make films will be cost effective and environment friendly compared to making films using additional chemicals.

3.6. Water retention

As seen from Table 4, the material treated with 1% NaOH has the highest water retention, followed by 5% NaOH, 0.5% NaOH and 5% NaOH/enzymes/1% NaOH. This is probably due to the hemicellulose content, the hydrophilicity of other impurities and the size and the number of particles in the materials. Since hemicelluloses are amorphous and highly hydrophilic, materials with higher hemicellulose content have high water retention. The material treated with 1% NaOH has the highest hemicellulose content and therefore the highest water retention whereas the material treated with 5% NaOH/Enzyme/1% NaOH has the

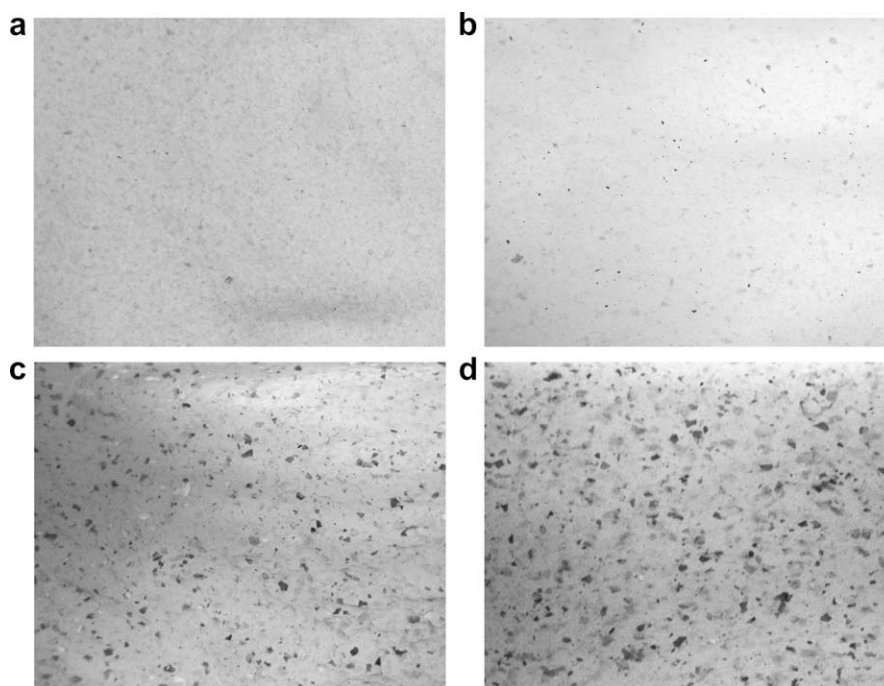


Fig. 5. Films made from oil and zein-free DDGS treated with various conditions. (a) 5% NaOH/enzymes/1% NaOH (b) 5% NaOH (c) 1% NaOH (d) 0.5% NaOH.

lowest hemicellulose content and hence the lowest water retention. The higher water retention of material treated with 5% NaOH despite having lower hemicellulose content than that of materials treated 0.5% NaOH is probably due to the lignin and the different size of particles in the materials. Lignin is hydrophobic compared to cellulose and therefore samples with higher lignin content have low water retention. In addition, the size of the particles in the materials also influences the water retention. The films shown in Fig. 5c and d have large particles that form a tight structure contributed by the strong linkage between cellulose, hemicellulose and lignin. The tight structure limits the water retention.

4. Conclusions

Cellulose has been purified from DDGS and corn kernels using alkali and enzymes with purity up to 81% and 72%, respectively. The cellulose obtained from DDGS has higher DP than cellulose from corn kernels but both the celluloses have similar % crystallinity. The presence of chemically linked hemicellulose in the crude cellulose obtained makes it possible to form films just using water without any chemicals. The extraction conditions can be varied to obtain crude cellulose with varying amount of impurities which formed films with different strength and elongation. However, it was found that an optimum amount of cellulose and hemicellulose was necessary to have adequate reinforcing and binding materials to obtain films with good strength and elongation. The presence of hemicellulose also causes the crude cellulose to absorb large amounts of water, up to 9 times the weight of the material. Cellulose obtained from DDGS may be used for applications such as films, composites, paper, water absorbents, lubricant and nutritional supplements.

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