

Structure and Mechanical Properties of Soy Protein Materials Plasticized by Thiodiglycol

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ABSTRACT: Thiodiglycol (TDG) is a relatively nontoxic compound from organic wastes. By using TDG as a plasticizer with weights from 2.5 to 40%, we prepared soy protein isolate (SPI) films by a compression-molding technique at 140°C and 15 MPa. The TDG-plasticized films (SPI-TDG films) were characterized by scanning electron microscopy, Fourier transform infrared spectroscopy, dynamic mechanical thermal analysis, thermogravimetric analysis, optical transmittance, and water uptake experiments. The SPI-TDG film plasticized with 25% TDG exhibited good mechanical properties, such as a tensile strength and modulus of 20.3 and 582 MPa, respectively, whereas the SPI-glycerol film with 25% glycerol had a tensile strength and modulus of 16.2 and 436 MPa, respectively. The results from the thermogravimetric analysis and water

uptake experiments indicated that the thermal stability and water resistance of the TDG-plasticized SPI materials were higher than that of the glycerol-plasticized one. The improvements in the mechanical properties, water resistance, and thermal stability of the SPI-TDG films could be attributed to the strong intermolecular hydrogen bonding between soy protein and TDG and the presence of fewer hydroxyl groups in TDG, as compared structurally with glycerol. This study provided a new plasticizer for the preparation of soy protein materials. © 2008 Wiley Periodicals, Inc. *J Appl Polym Sci* 111: 970–977, 2009

Key words: mechanical properties; thermal properties; proteins; films

INTRODUCTION

The use of synthetic plastics in our day-to-day life is one of today's major waste problems.¹ This is the reason biodegradable polymers produced from natural products have received considerable attention in terms of countering waste problems and sustainability.^{2–5} Among biopolymers, soy proteins have been considered for potential replacement of synthetic plastics because they can be converted into thermoplastics by solution casting, compression molding, or extrusion.^{6,7} They can also be converted into plastics with reduced water vapor permeability at ultrahigh pressures.⁸ Soy proteins have environmental benefits, but they often lack mechanical strength and water resistance properties. The processability and flexibility of soy proteins have been improved by the addition of plasticizers such as glycerol, ethylene glycol, triethylene glycol, poly(ethylene glycol), butane diols,^{9,10} urea,¹¹ and acetamide.¹² Glycerol

has been found to be a good plasticizer among polyols. However, the presence of three hydroxyl groups in glycerol leads to high water-absorbing properties in plasticized soy protein films. In addition, an increase in moisture sensitivity and a decrease in tensile strength has been observed with the addition of other types of plasticizers.^{13,14} To reduce water uptake, soy protein films have been investigated with either chemical modifications or by crosslinking reactions. The water resistance of plasticized soy protein films has been improved by the addition of suitable crosslinkers, such as furfural,¹⁵ formaldehyde,¹⁶ and dialdehyde starch.¹⁷ One of the simplest methods to improve the water resistance of the materials should be the search for a new plasticizer.

It is well known that sulfur is one of the heteroatoms prevalent in organic wastes found worldwide. One example of a particularly dangerous class of sulfur-containing wastes is distilled mustard (HD), which has the chemical formula $(\text{ClC}_2\text{H}_4)_2\text{S}$. Thiodiglycol [TDG or $(\text{OHCH}_2\text{CH}_2)_2\text{S}$] is the hydrolysis product of HD^{18,19} and is relatively nontoxic. As reported in the literature,^{18,19} it is slightly irritating to the eye and practically nonirritating to skin and is stable below 170°C. TDG has one less hydroxyl group than that of glycerol and is structurally similar to one of the amino acids, that is, cysteine (0.91%), in soy protein isolate (SPI).²⁰ In this study, TDG was investigated as a plasticizer for soy protein

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films. The effect of TDG on the mechanical properties, thermal behavior, and water uptake of SPI films were evaluated. Moreover, the structure, compatibility, and optical transmittance of the SPI films were also investigated. This article may contribute some meaningful information for the preparation of biodegradable soy protein materials with improved performance and the best utilization of organic wastes. TDG-plasticized SPI films may have potential applications in nonrecycled goods, such as trash/rubbish and compost bags and mulch films.

EXPERIMENTAL

Materials

SPI with a protein content of about 91% (dry basis) was purchased from Hubei Yunmeng Protein Technology Co. (Yunmeng, Hubei, China). The weight-average molecular weight of the SPI, which was determined by a multi-angle laser light scattering instrument equipped with a He-Ne laser ($\lambda = 632.8$ nm; DAWN1 DSP, Wyatt Technology Co., Santa Barbara, CA), was reported to be 2.05×10^5 .²¹ Glycerol was provided by Shanghai Chemical Co. (Shanghai, China). TDG (bp = 164–166°C, molecular weight = 122.19, and density = 1.182 g/cc) was purchased from Sigma-Aldrich (Seelze, Germany) and was used as received.

Preparation of the films

The SPI-TDG films, denoted S-T, were prepared by a compression-molding method. Different amounts of TDG (from 0 to 40% w/w with respect to SPI) were mixed with SPI powder separately in an electronic mixer for about 15 min. The resulting mixtures were subjected to hot pressing at 140°C for 20 min under 15 MPa of pressure. Two different approaches were used to prepare the compression-molded S-T films. By using TDG (20% or higher), we followed one step to prepare the films. It was difficult to prepare SPI films with TDG contents below 20%, so the SPI-TDG mixtures obtained in the first step were kept at 97% relative humidity (RH) for 6 h. In this case, water could also act as plasticizer for these samples. After taking the SPI-TDG mixtures from the 97% RH chamber, we again compression-molded the SPI-TDG mixtures at 140°C for 20 min under a pressure of 15 MPa to obtain the S-T films. The resulting films were designated S-XT, where S and T represent SPI and TDG, respectively, and X indicates the amount of TDG added with respect to SPI. For example, in sample S-25T, the content of TDG was 25%. All of the TDG-plasticized soy protein films were transparent, homogeneous, and yellow in color. At higher contents of TDG, the

obtained S-T films were flexible. At lower contents of TDG, the soy protein films were nonflexible.

SPI films prepared by solution-casting and compression-molding methods with glycerol as a plasticizer, denoted S-G, were compared with films prepared with TDG as a plasticizer with respect to the mechanical properties. The film coded S-25G, with 25% glycerol, was prepared in one step under the same condition as mentioned previously for the preparation of the S-25T sample. With the solution-casting method, the resultant SS-25G film, with 25% glycerol, was obtained. In a typical process, 2.5 g of glycerol was mixed with 10 g of SPI in a 0.1M NaOH solution. To denature the soy protein, 0.1M NaOH was added to the SPI dispersion to prepare the SS-25G film. The dispersion was mixed thoroughly with a magnetic stirrer for 1 h at 60°C. After that, the dispersion was poured into a Petri dish and dried in an air oven for 24 h to get the SS-25G film.

Leaching of TDG

An experiment was also conducted to investigate whether any TDG leached out from the S-T films as water-soluble residuals, and this was one reason we chose a new plasticizer. We obtained a calibration curve by plotting the absorbance (213 nm) versus concentration (0.02–0.1 g/L) of TDG by taking distilled water as a blank. An exact weight (~ 0.1 g) of different S-T samples was put in 10 mL of distilled water for 26 h. After 26 h, the S-T samples were taken out of the distilled water, and the absorbance of the aqueous solutions was determined with a spectrophotometer (Shimadzu UV-160A, Kyoto, Japan). The maximum absorption by TDG was found in the ultraviolet range, that is, at 213 nm; hence, the experiment was conducted to determine the leached TDG (if any) in the water-soluble residual solutions. The water-soluble residuals obtained from the SPI film were used as blanks in this study.

Characterization

Fourier transform infrared (FTIR) spectra of all the samples were obtained on a Nicolet 5700 FTIR spectrometer (Thermo Electron Co., Waltham, MA) in the range 4000–400 cm^{-1} with the KBr disk method. Scanning electron microscopy (SEM) images of S-5T, S-30T, and S-40T were taken on a field emission scanning electron microscope (Sirion, Hillsboro, OR) at an accelerating voltage of 30 kV. Dried films were frozen in liquid nitrogen and snapped immediately, and then, the cross-section surfaces of the films were coated with gold for SEM observations. The optical transmittances of the SPI films with TDG as a plasticizer were measured with an ultraviolet-visible spectrophotometer (UV-160A, Shimadzu) with

wavelengths of 400–800 nm. Dynamic mechanical thermal analysis (DMTA) was performed on a dynamic mechanical analyzer (DMAQ800, TA Instruments, Newcastle, DE) in tensile mode at a frequency of 1 Hz. The samples were $10 \times 10 \text{ mm}^2$ (length \times width), and the test temperature ranged from -100 to 220°C with a heating rate of $5^\circ\text{C}/\text{min}$. The α -relaxation temperature was determined as the peak value of the loss angle tangent.

The tensile strength, elongation at break, and Young's modulus of the films were measured on a universal testing machine (CMT6503, Shenzhen SANS Test Machine Co., Ltd., Shenzhen, China) with a tensile rate of $5 \text{ mm}/\text{min}$ according to ISO527-3: 1995 (E). An average value from five replicates of each sample was taken. Thermogravimetric analysis (TGA) of the dried films (ca. 5 mg) was carried out at a heating rate of $10^\circ\text{C}/\text{min}$ between room temperature and 700°C in a nitrogen atmosphere on a Pyris thermogravimetric analyzer linked to a Pyris diamond TA laboratory system (Perkin Elmer Co., Waltham, MA).

Two approaches were followed to determine the water absorption. In the first approach, at two different RHs, that is, 57 and 97%, the water absorption of the samples was determined. We determined the water uptake rate of the samples by putting the samples at 0% RH for about 72 h to obtain a constant weight and then again determining the final weight by putting the samples at 57% RH for 3 days. To determine the amount of water absorbed by the samples at higher RH, samples were also kept at 97% RH separately for 24 h and weighed. After taking the weight of the films at both RHs, we determined the water uptake. The water uptake of the films was calculated as follows:

$$\text{Water uptake (\%)} = \frac{W_t - W_0}{W_0} \times 100 \quad (1)$$

where W_0 represents the initial weight and W_t is the final weight of the samples after they were removed from the desiccator of a particular RH. The water uptake experiment at different RHs was done in triplicate, and the average value was reported. In the second approach, the water uptake of the samples was evaluated according to ASTM D 570-81. The samples were preconditioned at 50°C for 24 h then cooled in desiccators and weighed (W_0). The preconditioned specimens were immersed in distilled water at room temperature for 26 h. After that, the films were removed from water and dried with paper towels to remove the water on the surface of the films and again weighed (W_t). The containers with water-soluble materials were placed in an oven at 50°C for 48 h to evaporate the water. The residuals were the water-soluble contents. The weight gain of the films added

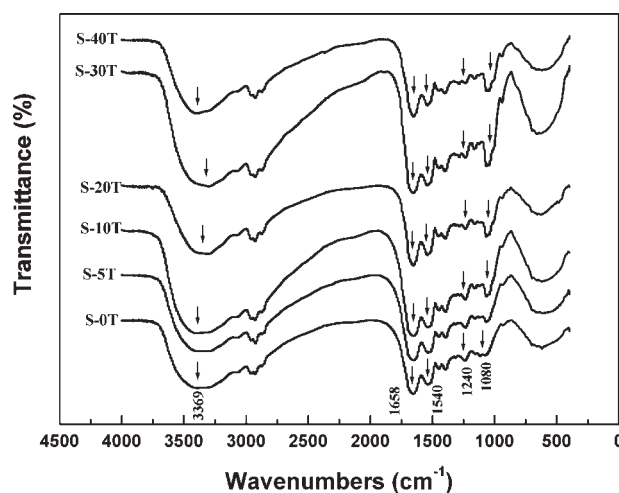


Figure 1 FTIR spectra of the S-T films with TDG contents ranging from 0 to 40% with respect to SPI.

to the weight of the water-soluble residuals (W_r) was counted as the total absorbed water. An average of three readings was reported. The water uptake of the films immersed in water was calculated as follows with a modification of eq. (1):

$$\text{Water uptake (\%)} = \frac{(W_t + W_r) - W_0}{W_0} \times 100 \quad (2)$$

RESULTS AND DISCUSSION

Structure and compatibility of the films

Figure 1 shows the FTIR spectra of the S-T films. The broad N-H stretching band between 3200 and 3400 cm^{-1} was assigned to amide A of protein. N-H bending and C-N stretching at 1540 and 1240 cm^{-1} , respectively, were assigned to the amide II and amide III bands of protein. The band at 1080 cm^{-1} was due to -OH deformations in alcohol, namely, TDG. The intensity of the band at 1080 cm^{-1} increased with the incorporation of TDG in SPI, which indicated the existence of TDG. The protein structure was considered a random coil with an absorption band from 1655 to 1658 cm^{-1} .²² All of the S-T infrared scans displayed a band at 1658 cm^{-1} , which indicated this type of structure. The broad peaks for S-30T and S-40T shifted to significantly higher wave numbers and changed into relatively sharp peaks. This suggested that the hydrogen bonding interaction between the proteins themselves was weakened as a result of the addition of the high amount of TDG.

Figure 2 shows the morphology of the S-T films. The S-30T film showed an almost homogeneous surface and a cross section exhibiting a coarser surface [Fig. 2(b)]. However, the S-5T [Fig. 2(a)] and S-40T [Fig. 2(c)] films, with lower and higher amounts

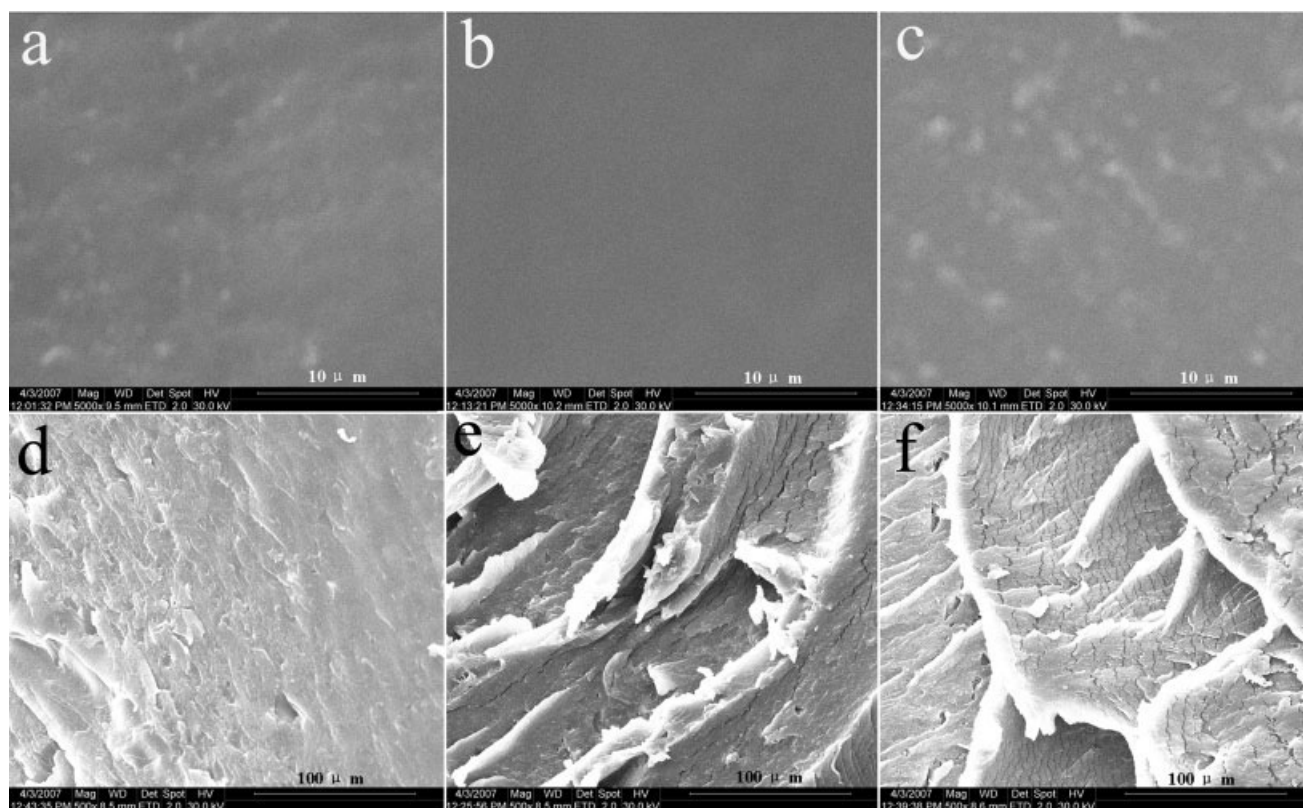


Figure 2 SEM images of the surfaces of (a) S-5T, (b) S-30T, and (c) S-40T and cross sections of (d) S-5T, (e) S-30T, and (f) S-40T.

of TDG, respectively, exhibited a relatively less homogeneous surface. The coarser surface in the cross section of the fractured S-T film with higher TDG content could have been relative to the excessive weakening of protein-protein interactions. This was in a good agreement with the conclusions from the FTIR results. Moreover, similar behavior has been reported for protein plasticized by polyols such as 1,2-butanediol, 1,3-butanediol, glycerol, and propylene glycol.²³ In addition, the cross section of the plasticized films showed a multilaminar structure for S-30T and S-40T, as shown in glycerol-plasticized starch films.²⁴

DMTA of the S-T samples were carried out to provide information on the segmental motion of the protein molecules. Figure 3 shows the temperature dependence of the loss factor of the S-T films. The high α -relaxation temperatures were assigned to protein-rich domains. Interestingly, only one α -relaxation value was observed for the TDG-plasticized SPI films. The α -relaxation temperatures showed a significant decrease from 165.2 to 98.7°C with increasing TDG content from 10 to 40%, respectively. The decrease in the α -relaxation temperature at higher contents of plasticizer suggested an increase in the molecular mobility of the protein molecules. This indicated that TDG had a better plasticizing efficiency at a higher content (20%) than at a lower con-

tent (10%). Therefore, the flexibility of the S-T films increased with increasing content of plasticizer in the SPI films.

The optical transparency of a material is one criterion for judging the compatibility of additives in the matrix.²⁵ Figure 4 shows the dependence of the optical transmittance percentage on the TDG content of the S-T films. The unplasticized SPI film showed a very low optical transmittance (29.4%). A lower amount of plasticizer in the soy protein resulted in

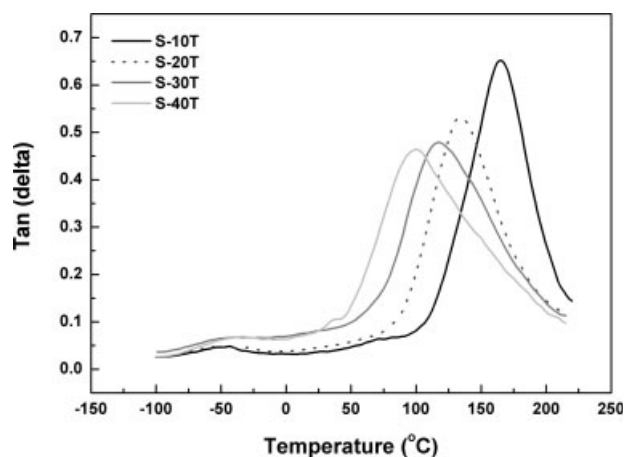


Figure 3 Temperature dependence of the loss peaks (tan δ) for the S-T films with different contents of TDG.

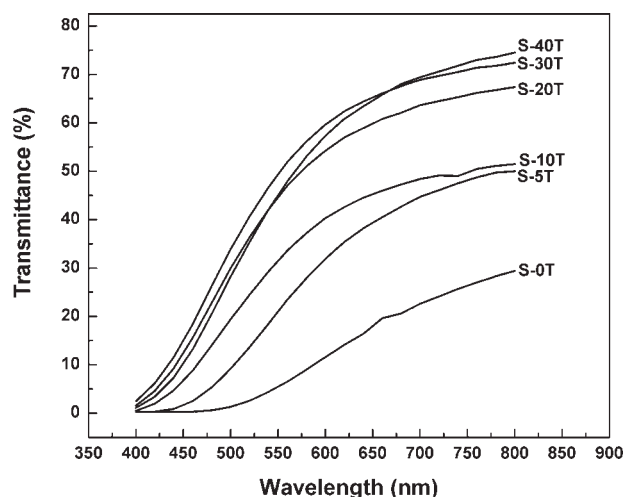


Figure 4 Optical transmittance (%) curves of the S-T films with different contents of TDG.

thicker S-T films; this could have been responsible for the lower optical transmittance values because of the restricted mobility of the protein molecules at lower contents of plasticizer, which was well confirmed in Figure 3. The optical transmittances of the S-T films above 20% TDG content were $68 \pm 5\%$, which indicated a higher degree of compatibility between SPI and TDG and a better plasticization effect.

Mechanical properties

Usually, the mechanical properties of soy protein plastics are influenced by the amount of plasticizer and the water content in the samples. Figure 5(a) shows the stress-strain curves of the S-T films at 57% RH. As the content of TDG increased from 20 to 40%, the tensile strength decreased, whereas the elongation at break increased. With increasing TDG content from 20 to 40%, the behavior of the SPI plastics changed from hard and brittle to soft and weak. The modulus also exhibited a decrease with increasing content of TDG [Fig. 5(b)]. The tensile strength and modulus of the S-25T sample were about 20.3 and 582 MPa, respectively, whereas those of the S-25G film, with 25% glycerol, were about 16.2 and 436 MPa, respectively. This indicated that the tensile strength of the S-T films improved compared with the S-G film. Interestingly, the SS-25G sample, with 25% glycerol, prepared by the solution-casting method showed a very high elongation at break ($\sim 250\%$), which was higher than that of the compression-molded samples plasticized by either 25% TDG or glycerol. The higher elongation at break for the solution cast sample was due to the presence of absorbed water, which acted as a plasticizer. However, its tensile strength (~ 4 MPa) and modulus (~ 30 MPa) were very low. Liu et al.¹² reported a

tensile strength, modulus, and elongation at break of about 8 MPa, 100 MPa, and 65%, respectively, for an SPI film plasticized by 25% acetamide at 35% RH. A tensile strength of about 8.6 MPa and a modulus of about 248 MPa were observed for a 25% stearic acid modified glycerol (20%) plasticized film at 65% RH.²⁶ Therefore, our results indicate that TDG imparted better improvements in the mechanical properties compared to glycerol and stearic acid.

Figure 6(a) shows the stress-strain curves of S-T films with TDG contents higher than or equal to 20% with respect to SPI at 97% RH. All of the S-T films with TDG contents that were higher than or equal to 20% exhibited soft and weak behavior at 97% RH. As the content of TDG with respect to SPI increased from 20 to 40%, the tensile strength and modulus showed a decreasing trend. The elongation at break increased at higher contents of TDG [Fig. 6(b)]. This indicated that the mechanical properties of the S-T films were significantly affected at 97% RH because of the absorption

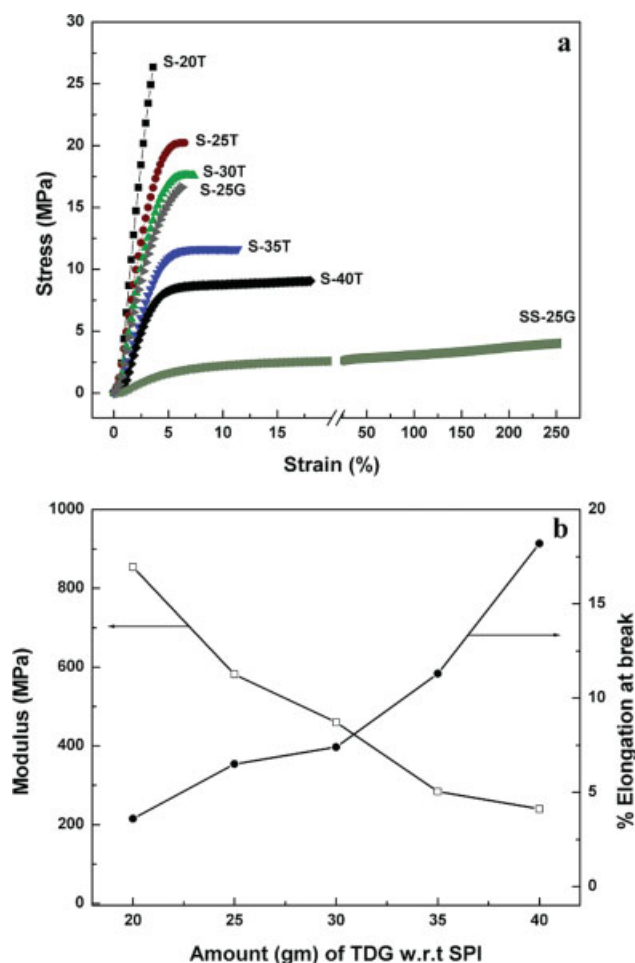


Figure 5 (a) Stress-strain curves and (b) modulus and elongation at break of the S-T films with TDG contents greater than or equal to 20% with respect to SPI at 57% RH. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

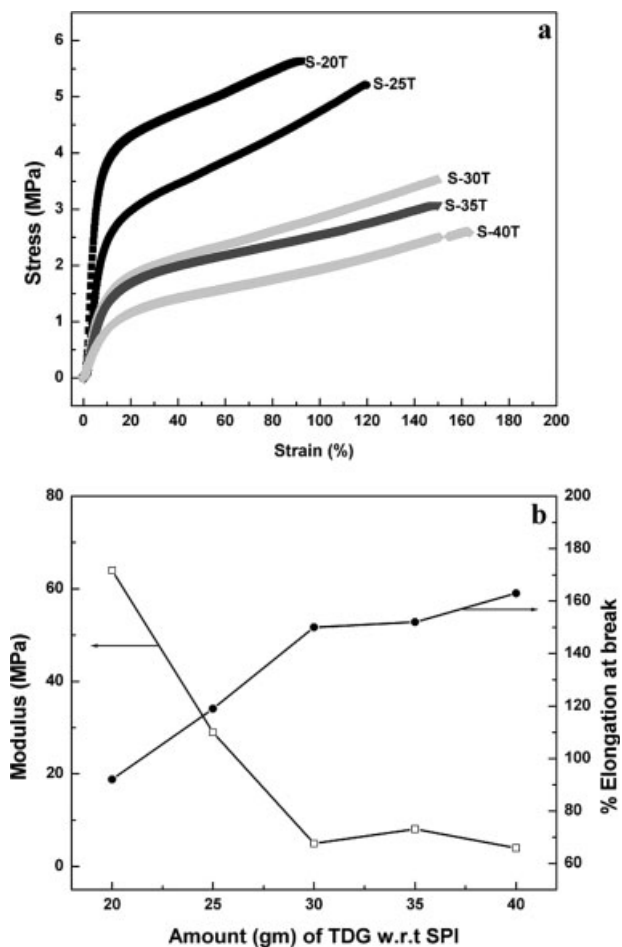


Figure 6 (a) Stress–strain curves and (b) modulus and elongation at break of the S–T films with TDG contents greater than or equal to 20% with respect to SPI at 97% RH.

of water. Therefore, RH was one important factor that affected the material performance of the protein films. At higher RH, absorbed water in the protein films also acted as a plasticizer in addition to the added plasticizer and thereby decreased the tensile strength and modulus while increasing the elongation of the protein films. The same trend was observed for the S–T films kept at higher RH.

Figure 7(a) shows the stress–strain curves of the S–T films with TDG contents lower than 20%. We already mentioned that the S–T films were very brittle below 20% TDG and the films displayed a break when they were fixed in the grip of the tensile testing machine. Hence, the samples were conditioned at 97% RH for 24 h before the experiment was performed. The tensile strength and modulus of sample S–0T were about 12 and 533 MPa, respectively, whereas those of the S–5T film were the highest (tensile strength \approx 17.5 MPa and modulus \approx 638 MPa at 97% RH). At lower amounts of TDG, the greater thickness (0.75 ± 0.1 mm) of the S–T films may also have been responsible for the better mechanical properties. This suggested that lower amounts of

TDG helped to obtain hard and brittle films, whereas TDG contents higher than 7.5% gave soft and weak properties to the SPI plastics. The percentage elongation at break of S–T films also increased from 2.8 to 99.6% at 97% RH with increasing TDG content from 5 to 15% [Fig. 7(b)].

The amount of water absorbed by the S–T samples kept at two different RHs before the experiment was performed was determined. The water uptake of the S–T samples kept at 57% RH for 3 days was very low compared to the same samples kept at 97% RH for 24 h. At 57% RH, the water uptake of S–T was $0.5 \pm 0.25\%$, whereas at the 97% RH water uptake of S–T was $3.5 \pm 1\%$. No definite trend of increasing water uptake was observed in the S–T samples with TDG contents lower than 20%, and the results were within the error limit. This may have been due to a lower plasticization effect and restricted flow behavior of the TDG in the SPI during the processing of the films (Fig. 3).

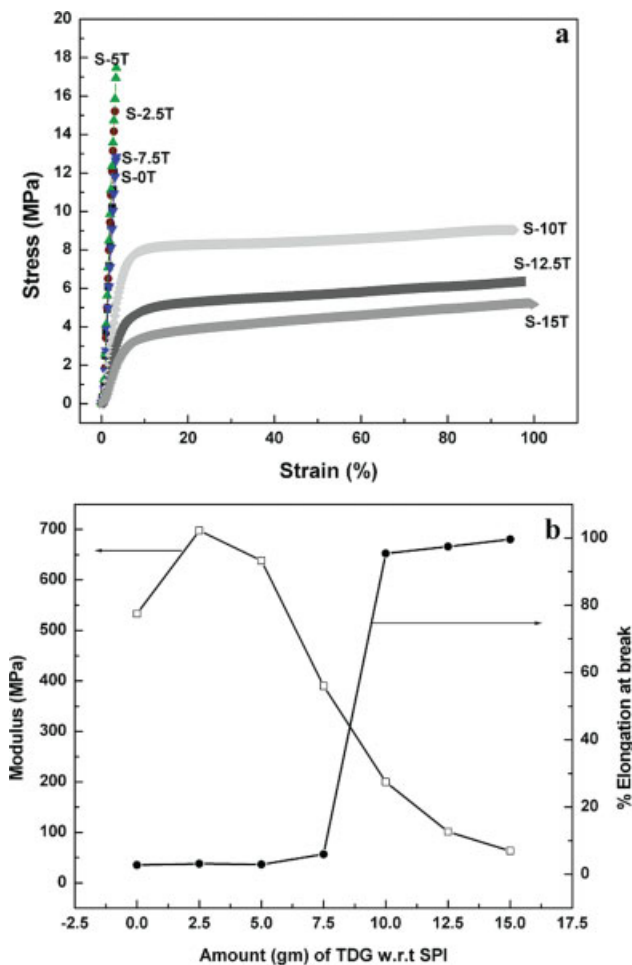


Figure 7 (a) Stress–strain curves and (b) modulus and elongation at break of the S–T films with TDG contents lower than 20% with respect to SPI at 97% RH. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Thermal behaviors of the films

Figure 8 shows the TGA and differential thermo-gravimetry (DTG) traces of the S-T films. The results obtained from the TGA and DTG curves of the S-T films are shown in Table I. The weight losses of the samples in the temperature ranges 50–200, 200–300, and 300–400°C, as well as the temperature at the maximum rate of mass loss (T_{\max}), were determined. All of the films, except S-0T to S-5T, exhibited two T_{\max} values, designated $T_{\max1}$ for the temperature range 200–300°C and $T_{\max2}$ for the temperature range 300–400°C. The weight loss of 4–16% below 200°C was attributed to the evaporation of adsorbed moisture. The boiling point of TDG was 164–166°C, but from the valley of the DTG curves, no peak was observed around this temperature. This fact indicated that some kind of interactions (hydrogen bonds) existed between the SPI and TDG molecules. The maximum rate of TDG weight loss determined by the valley of the DTG curves (Table I) first reached at 245°C for S-12.5T then shifted to 253°C for S-20T and finally dropped to 228°C when the TDG content reached 40%. $T_{\max1}$ was higher than

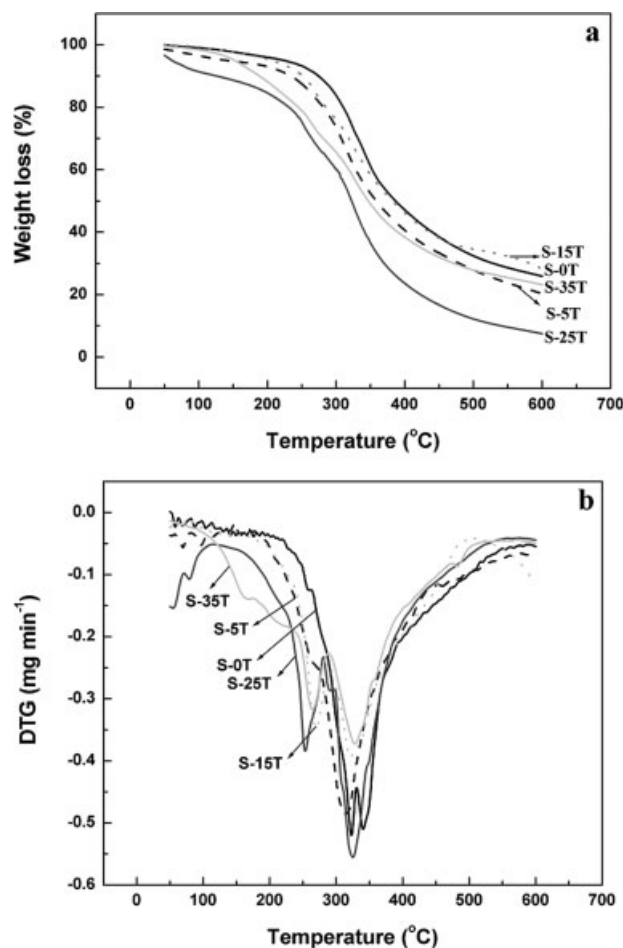


Figure 8 (a) TGA and (b) DTG curves of the S-T films with different contents of TDG.

TABLE I
Weight-Loss and T_{\max} Values for S-T Samples with Different TDG Contents

Sample	WL0 (%)	WL1 (%)	$T_{\max1}$	WL2 (%)	$T_{\max2}$	WL1 + WL2 (%)
S-0T	4.0	14.7	—	34.6	305 331	49.3
S-2.5T	6.7	21.2	—	30.7	305	51.9
S-5T	6.7	21.2	—	25.4	300	46.6
S-7.5T	8.0	21.3	245	30.6	297	51.9
S-10T	5.3	22.6	245	28.0	300	50.6
S-12.5T	6.7	22.6	245	24.0	297	46.6
S-15T	4.0	21.3	253	28.0	303	49.3
S-20T	4.0	15.9	253	38.7	315	54.6
S-25T	15.9	13.4	241	46.6	313	60.0
S-30T	12.0	27.9	244	25.4	315	53.3
S-35T	12.0	25.3	236	33.3	309	58.6
S-40T	16.0	29.3	228	22.6	301	51.9

WL0 = initial weight loss (50–200°C); WL1 = weight loss 1 (200–300°C); WL2 = weight loss 2 (300–400°C).

the boiling point of TDG. There was a 60–70°C increase in the value of $T_{\max1}$ compared to boiling point of TDG. Recently, from our laboratory, a 15–25°C increase in the value of $T_{\max1}$ was reported compared with boiling point of glycerol.¹⁴ In acetamide-plasticized soy protein sheets, $T_{\max2}$ decreased from 326 to 321°C with increasing acetamide content from 20 to 50 phr.¹² The SPI film showed two $T_{\max2}$ values at 305 and 331°C. With the incorporation of TDG in soy protein, the higher $T_{\max2}$ disappeared, and the DTG curve merged into one. Again, the maximum rate of TDG weight loss determined by the valley of the DTG curves first reached at 305°C for S-2.5T then shifted to 315°C for S-20T and finally dropped to 301°C when the TDG content reached 40%. The increase in the T_{\max} values at lower contents of plasticizer and decrease in T_{\max} values at higher contents of plasticizer were in good agreement with glycerol- and acetamide-plasticized SPI sheets.^{12,14} Thus, there was a change in the thermal degradation behavior of the soy protein films with the incorporation of TDG. The increased thermal stability indicated that the interaction between TDG and SPI was stronger than that of glycerol and SPI.¹⁴ The total mass loss obtained for all of the S-T films between 200 and 300°C and 300–400°C was $55 \pm 8\%$.

Water resistance of the films

The water resistance of samples can be evaluated by water uptake. Figure 9 shows the water uptake values of the S-T films, after the samples were taken from distilled water after 26 h. Interestingly, the S-T films displayed lower water absorption values than the unplasticized SPI film. For the SPI film, the water uptake was high ($116 \pm 3\%$). As the TDG content increased from 2.5 to 10%, the water uptake

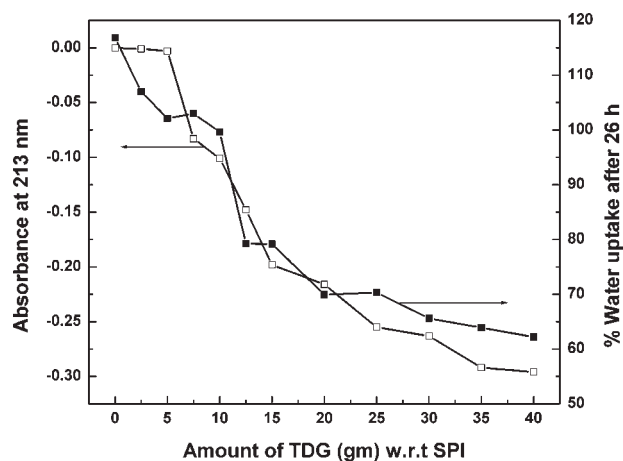


Figure 9 Water uptake and absorbance of the S–T films after their immersion in distilled water for 26 h.

value decreased from $106 \pm 1\%$ to $100 \pm 1\%$. Above a 30% TDG content, the water uptake value of SPI–TDG was $63 \pm 2\%$. The total soluble material left in the container for sample S–0T was very low, that is, $0.20 \pm 0.05\%$. With increasing TDG content, the total soluble material further decreased to $0.12 \pm 0.05\%$ for the S–40T sample. The water uptake of SPI–polyol samples, as reported, was very high because of the difference in the processing method.²³ Interestingly, it has been reported that compression-molded 0.5% sodium dodecyl sulfate modified SPI plastic showed a high water uptake of 542%, and it further increased to 1446% with increasing sodium dodecyl sulfate concentration to 5%.²⁷ The water uptake of the S–25G sample, processed under the same conditions as the S–T films, was 77%. Therefore, the S–T films exhibited relatively good water resistance. Moreover, different concentrations of TDG (0.02–0.1 g/L) were prepared, and the absorbance was taken at 213 nm. An experiment was carried to determine the maximum absorption of TDG between 200 and 400 nm. A soluble material solution of S–0T without TDG was used as a blank to determine the absorbance of soluble material solutions of different S–T films. A decrease in the absorbance of the soluble material solution was observed (Fig. 9) compared to the control sample (S–0T). This suggested that TDG formed a strong linkage via hydrogen bonds with the soy protein, which thereby prevented the dissolution of low-molecular-weight soy protein and the leaching of TDG, as observed in the films prepared from soy protein and glycerol.²⁶

CONCLUSIONS

TDG as a new plasticizer was successfully used to plasticize soy protein materials. The results from SEM, optical transmittance, DMTA, and FTIR testing

indicated that a good compatibility occurred between TDG and the soy protein. A decrease in the α -relaxation temperature with an increase in the content of plasticizer suggested the restricted mobility of the protein molecules at lower contents of plasticizer. The mechanical properties of the TDG-plasticized SPI films were better than those of the glycerol-plasticized films. Moreover, the S–T films with high contents of TDG exhibited good mechanical properties and thermal stability. The absorbance of the water-soluble material solution of S–T films decreased with increasing TDG content, which indicated that the leaching of TDG did not take place. It also indicated that the S–T films possessed good water resistance properties. Thus, TDG as a plasticizer of soy protein films could improve their thermal stability, water resistance, and mechanical properties compared to commonly used plasticizers such as glycerol.

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