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# Mechanical, barrier and morphological properties of pea starch and peanut protein isolate blend films

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ABSTRACT

Mechanical, barrier and morphological properties of edible films based on blends of Pea starch (PS) and Peanut protein isolate (PPI) plasticized with glycerol (30%, w/w) were investigated. As PPI ratio in PS/PPI blends increased, the thickness of films decreased, the opacity slightly elevated and color intensified. The addition of PPI to the PS film significantly reduced tensile strength from 5.44 MPa to 3.06 MPa, but increased elongation from 28.56% to 98.12% with the incorporation of PPI into PS at 50% level. Film solubility value fell from 22.31% to 9.78% upon the incorporation of PPI ranged from 0 to 50% level. When PPI was added into PS film at 40% level, the WVP and WVTR of the films markedly dropped from 11.18% to 4.19% and 6.16 to 1.95%, respectively. Scanning electron microscopy (SEM) of the surface of films showed that many swollen starch granules were presented in the 100% PS film, while 100% PPI film was observed to have rougher surfaces with presence of pores or cavities. The PS/PPI blend films upon the incorporation of PPI at 20% and 50% level were not homogeneous. However, the smoother film surface was observed in PS/PPI blend films with the addition of PPI at 40% level. SEM image of the cross-sections of the films revealed that the 100% PS film showed a uniform and compact matrix without disruption, and pore formation and 100% PPI film displayed a smooth structure. Rougher and flexible network was shown in blend film with the addition of PPI reaching 40% level.

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## 1. Introduction

Petroleum-based food packaging has been widely used to maintain the quality of products and prolong their shelf-life. However, environmental concerns about petroleum pollutions and oil scarcity require alternative substitutions (Jansson, Jarnstrom, & Ratto, 2006). Over the past decade, a large amount of research has been devoted to edible and biodegradable films (Maran, Sivakumar, Sridhar, & Thirugnanasambandham, 2013). Components of edible films and coatings can be divided into three categories: hydrocolloids, lipids, and composites. In terms of composition, hydrocolloids can be either carbohydrates or proteins.

Starch contains linear polymers of amylose and branched polymers of amylopectin. The starch film property changes with amylose to amylopectin ratio. Pea starches (PS) are characterized by high amylose content, mostly ranging between 30% and 60% and varying with species (Hoover, Hughes, Chung, & Liu, 2010). Therefore, pea starch is a very useful film-forming material because of its high amylose content which can improve mechanical strength, including tensile strength (TS) and gas barrier properties (Palviainen et al., 2001).

References have been reported about characteristics of PS film (Zhang & Han, 2006a, 2006b, 2008; Corrales, Han, & Tauscher, 2009; Dai, Chang, Yu, Ma, & Zhou, 2010; Fabunmi, Tabil, Panigrahi, & Chang, 2011; Mehyar, Al-Ismail, Han, & Chee, 2012). Since 100% PS films are brittle and have poor performance of water vapor barrier, they are not used extensively in food packaging. Widespread use of these films will partly depend on the development of films with improved performance.

Among several polymers, proteins extracted from plants attract special attention in the production of biodegradable polymers. According to Kokoszka, Debeaufort, Hambleton, Lenart, and Voilley (2010), protein films, in general, have good moisture resistance because of inherent hydrophobicity of the protein and the substantial amounts of hydrophilic plasticizer used to impart film flexibility. Soy protein isolate (Mariani, Allganer, Oliveira, Cardoso, & Innocentini-Mei, 2009.) and soybean protein concentrate (De la Caba et al., 2012) have been used to improve starch-based films. The cassava starch and soy protein concentrate based edible films has been developed (Chinma, Ariahu, & Abu, 2012). The characterization of edible coatings consisting of whey protein isolate and pea starch has also been studied (Mehyar et al., 2012).

China is one of the largest producers of peanut, accounting for 46.5% of total peanut production worldwide (Jamdar et al., 2010).

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Peanut seed contains 25–29% protein, 20–23% carbohydrate and 40–50% oil (Latifa, Pfannstielb, & Makkara, 2013). Defatted peanut flour is a byproduct generated after extracting oil from peanuts, which contains 47–55% of proteins but with poor functional properties (Yu, Aahmedna, & Goktepe, 2007). Peanut protein (Reddy, Chen, & Yang, 2013) has been used to prepare protein films. However, peanut protein isolate (PPI) (a product prepared by alkali dissolution and acid precipitation from defatted peanut flour), has higher purity of proteins and better functional properties than other peanut protein products, such as flour or concentrate (Wu, Wang, Ma, & Ren, 2009).

The combination of PPI and PS would be an attractive method to develop new edible films by drawing advantages of the PS and PPI components and minimize their disadvantages. To the best of our knowledge, there are no reports on the properties of PS/PPI blend films so far. This partly stimulated this research. Data obtained from this study, might be useful for new edible film preparations.

## 2. Materials and methods

### 2.1. Materials

Pea starch (approximately 40% amylose and 60% amylopectin) was purchased from the National Starch Co. (Shanghai, China). The defatted peanut flour was kindly provided by Changshou Group Co. Ltd. (Shandong, China). Glycerol was purchased from Sigma–Aldrich (St. Louis, MO., China).

### 2.2. Preparation of PPI

The alkaline extraction and acid precipitation method described by Kim, Kim, and Nam (1992) was used to prepare PPI. The defatted peanut flour was mixed with distilled water at the ratio of 1:10, adjusting the pH to 9.0 with 1 N NaOH, and stirred at 40 °C in a water bath for 1 h with the stirring speed of 100 rpm. After the extraction process, the suspended material was filtered through a 100-mesh standard sieve. The resulting supernatant was adjusted to pH 4.5 with 1 N HCl and centrifuged at 4000 rpm for 15 min. The precipitates were then washed with distilled water and centrifuged several times at 4000 rpm for 15 min until a pH of 7.0 was reached. PPI was then dried at 40 °C for 48 h in an air oven, ground to pass through 100-mesh standard sieve and stored at 4 °C from where samples were drawn for analysis.

### 2.3. Formulation of PS/PPI blends

PS and PPI were mixed at different ratios (100:0%, 90:10%, 80:20%, 70:30%, 60:40% and 50:50%) using a mixer (Vortex. Genie2, Scientific Industries, American).

### 2.4. Preparation of glycerol-plasticized PS/PPI composite films

Films were produced according to the formulations shown in Table 1. The method of preparation was adapted from Araujo-Farro, Podadera, Sobral, and Menegalli (2010). Glycerol at 50% level on the dry basis of total solid content in film solution, as a plasticizer, was dispersed into 100 mL of PS/PPI composite suspensions with magnetic stirring (250 rpm) at room temperature for 1 h. Glycerol-plasticized PS/PPI composite solutions were brought to boiling water bath with continuous agitation for 30 min to allow full gelatinization of the blends. After the heating period, PS/PPI composite solutions were degassed under vacuum (1.0 MPa) for 10 min and cooled down to room temperature. Film forming dispersions (about 65 g) were spread evenly over Petri dishes (15 cm diameter) resting on a level surface. Films were formed by drying at 25 °C in a air circulating-oven until reaching constant weight (about 24 h).

**Table 1**
Formulations used in the production of the films.

| Sample | PS (g) | PPI (g) | Glycerol (g) | Distilled water (mL) |
|---|---|---|---|---|
| $F_{100:0}$ | 5.0 | – | 1.5 | 100 |
| $F_{80:20}$ | 4.0 | 1.0 | 1.5 | 100 |
| $F_{60:40}$ | 3.0 | 2.0 | 1.5 | 100 |
| $F_{50:50}$ | 2.5 | 2.5 | 1.5 | 100 |
| $F_{0:100}$ | – | 5.0 | 1.5 | 100 |

$F_{100:0}$, $F_{80:20}$, $F_{60:40}$, $F_{50:50}$ and $F_{0:100}$ means the mixed ratio of PS/PPI on a dry basis were 100:0, 80:20, 60:40, 50:50 and 0:100, respectively.

### 2.5. Thickness of PS/PPI composite films

The thickness of films was determined using a digital micrometer (Venier, China, 0.001 mm accuracy). Reported thickness values were the mean value of ten measurements for each film sample. The average value for each film was used to assess the opacity of the produced films and calculate the tensile properties and the water vapor permeability.

### 2.6. Optical properties

The transparency of the films were determined by measuring their light absorption at wavelength of 600 nm, using a UV-Visible spectrophotometer Shimadzu 1601 PC (Tokyo, Japan), according to the method described by Maran et al. (2013). The film specimens were cut into strips (1 cm × 4 cm) and placed directly in the spectrophotometer test cell. Air was used as reference. Film opacity was expressed as the area under the integrated recorded curve. Opacity was expressed as absorbance units per thickness unit. Three replicates of each film were tested.

### 2.7. Color measurement

Sample surface color was analyzed with a colorimeter (CR-400 Minolta Chroma Meter; Konica Minolta Sensing Inc., Tokyo, Japan) according to the method described by Jang, Shin, and Song (2011) with some modifications. Samples (50 mm × 50 mm strips) were placed onto a white standard plate, and Hunter values ($L^*$, $a^*$ and $b^*$) were measured. The Hunter $L^*$, $a^*$, and $b^*$ values for the standard plate were $L^* = 96.68$, $a^* = 0.14$, and $b^* = 1.94$.For each sample, five measurements were taken at different locations.

### 2.8. Mechanical properties

A TA.XT Plus Texture Analyzer (Lloyd Instruments, West Sussex, England) was used to determine the tensile strength and percentage of elongation at break. Film specimens were tested as suggested by Mehyar et al. (2012) with some modifications and the tests were carried out according to the ASTM D828-97 standard test methods (ASTM, 1997). PS/PPI composite films were cut into strips (1 cm × 10 cm). The strips were then preconditioned at 67% RH for 48 h inside a sealed deccicator containing saturated sodium chloride solution at room temperature (25 ± 1 °C). At least three replications of each test sample were performed and average values of the measurements were used. The films were loaded into the testing system, which was set at an initial sample length and grip speed of 2 cm and 100 mm/min, respectively. Tensile strength (MPa) was calculated by dividing maximum load by cross-sectional area of the film. Percent elongation at break was expressed as percentage of change of the original length of a specimen between grips at break.

**Table 2**
Optical properties and color values of PS/PPI blend films.

| Sample | Thickness (μm) | Opacity | $L^*$ | $a^*$ | $b^*$ |
|---|---|---|---|---|---|
| $F_{100:0}$ | 115.07 ± 3.09[a] | 2.16 ± 0.02[e] | 96.11 ± 0.12[e] | 0.06 ± 0.01[e] | 1.96 ± 0.11[e] |
| $F_{80:20}$ | 102.33 ± 1.73[b] | 3.21 ± 0.10[d] | 94.23 ± 0.22[d] | 0.60 ± 0.04[d] | 3.58 ± 0.05[d] |
| $F_{60:40}$ | 93.13 ± 2.51[c] | 4.19 ± 0.18[c] | 91.95 ± 0.25[c] | 1.11 ± 0.09[c] | 5.51 ± 0.25[c] |
| $F_{50:50}$ | 82.40 ± 2.30[d] | 4.94 ± 0.12[b] | 89.74 ± 0.18[b] | 1.30 ± 0.08[b] | 6.90 ± 0.16[b] |
| $F_{0:100}$ | 71.07 ± 1.38[e] | 5.59 ± 0.08[a] | 81.82 ± 0.09[a] | 4.48 ± 0.02[a] | 11.8 ± 0.43[a] |

$F_{100:0}$, $F_{80:20}$, $F_{60:40}$, $F_{50:50}$ and $F_{0:100}$ means the mixed ratio of PS/PPI on a dry basis were 100:0, 80:20, 60:40, 50:50 and 0:100, respectively.
Within the same columns, values with different superscripts letters (a, b, c, d and e) differ ($P < 0.05$).

### 2.9. Film solubility

Water solubility of each film was measured as described by Rhim, Lee, and Kwak (2005) with some modifications. Three randomly selected samples from each film were first dried at 105 °C for 12 h to determine the initial dried film. Then, they were placed in a 50 mL centrifuge tube containing 40 mL of distilled water and stored at room temperature for 24 h with occasional gentle stirring. Undissolved dry film was determined by removing the film pieces from the tubes and gently rinsing them with distilled water, and oven drying them (105 °C, 12 h). The film solubility (%) = $(W_b - W_a)/W_b \times 100$, where $W_b$ is the dry weight of the sample before submersion and $W_a$ is the dry weight of the sample after submersion.

### 2.10. Measurement of water vapor permeability (WVP) and water-vapor transmission rate (WVTR)

Before the testing, films were conditioned at 25 °C for 48 h in a desiccator with a relative humidity of 67% (saturated solution of sodium chloride). The gravimetric method was used to determine WVP and WVTR of PS/PPI blend films and the tests were carried out according to the ASTM E96-00 (ASTM, 2000) methodology. Circular film samples at about 10 mm of diameter were placed over the mouth of the test cup and sealed by melt paraffin. The cup was prefilled with anhydrous calcium chloride leaving 3 mm to the top. After the film specimens were equipped, the assembly was weighed and placed in a chamber conditioned at 25 °C and 100% RH. Weight increments of the cup were measured and plotted at intervals. The slope of the straight line was calculated with a linear regression. The WVP was calculated as follows:

$$\mathrm{WVP} = \frac{m \times d}{A \times t \times P}$$

$$\mathrm{WVTR} = \frac{m}{A \times t}$$

where $d$ is film thickness (m), $m$ is the weight increment of the cup (g), $A$ is the area exposed ($m^2$), $t$ is the time lag for permeation (h), and $P$ is water vapor partial pressure difference across the film (Pa). All specimens were tested three times.

### 2.11. Scanning electron microscopy (SEM)

The films external surfaces and cross sections were observed with a JSM-5610LV SEM (JEOL, Tokyo, Japan), respectively, according to the description of De la Caba et al. (2012). Prior to the observation, the surfaces were sputter-coated with a gold layer to avoid charging under the electron beam. The films were frozen in liquid nitrogen and then fractured immediately. The fracture surfaces were sputtered with gold and then photographed.

### 2.12. Statistical analysis

All the data obtained were average values of triplicate determinations and subjected to statistical analysis of variance (ANOVA). Least significant differences ($P < 0.05$) were accepted among the treatments.

## 3. Results and discussion

### 3.1. Optical properties films

Thickness, opacity and color values of PS/PPI blend films are shown in Table 2. The incorporation of PPI resulted in a decrease in film thickness when compared to that of the control sample. According to Nobrega, Olivato, Grossmann, Bona, and Yamashita (2012), when a film did not have enough elasticity to undergo expansion, its structure was broken with the air flow, which led to a thicker film. Starch films had sticker structures than protein films, which resulted in higher thickness.

The film opacity values were used to assess the transparency of the films. According to Jimenez, Fabra, Talens, and Chiralt (2012), films based on starch are transparent, odorless, tasteless, and colorless. Reddy et al. (2013) reported that thermoplastic films from peanut proteins extracted from peanut meal were transparent indicating that the peanut proteins melted and formed a thermoplastic film. With increasing PPI ratio in PS/PPI composites, opacity of films slightly increased. Film opacity is sensitive to various factors including film thickness and color. In this study, it was observed that the average thickness decreased and color intensified as the concentration of PPI increased, which resulted in the lower transparency. Al-Hassan and Norziah (2012) reported that further increase of gelatin concentration in glycerol plasticized sago starch/fish gelatin films exhibited significantly higher absorbance than 100% sago starch film. Yoo and Krochta (2012) found that the addition of whey protein isolate into corn starch/methylcellulose blend film resulted in lower light transmission. In general, higher light absorbance of films related to desirable properties of edible films since it was an excellent barrier to prevent light-induced lipid oxidation when applied in food system, which was in line with by Gomez-Guillen, Ihlb, Bifanib, Silvab, and Montero (2007).

100% PS film had the lightest color ($L^* = 96.11 \pm 0.12$). The addition of PPI into PS solution increased the $L^*$ values, which indicated PS/PPI blend films were darker in color. Incorporation of PPI increased film yellowness as evidenced by increased $a^*$ (red) and $b^*$ (yellow) color values. The results may be due to the Maillard reaction between PS and the amino group in PPI. According to Cheftel, Cuq, and Lorient (1985), the yellow coloration associated with protein–aldehyde interactions was due to the various intermediate or final products of the Maillard reaction.

### 3.2. Mechanical properties of the films

Fig. 1 shows the results of the mechanical tests in terms of tensile strength and elongation at break of the PS/PPI composite films, respectively. The 100% PS film ($F_{100:0}$) showed the highest tensile strength but lowest elongation, while PPI film ($F_{0:100}$) had the contrary results. The higher tensile strength of the PS film than other films may be due to its high content of amylose (40%). Kramer (2009) reported that amylose is linear and forms an

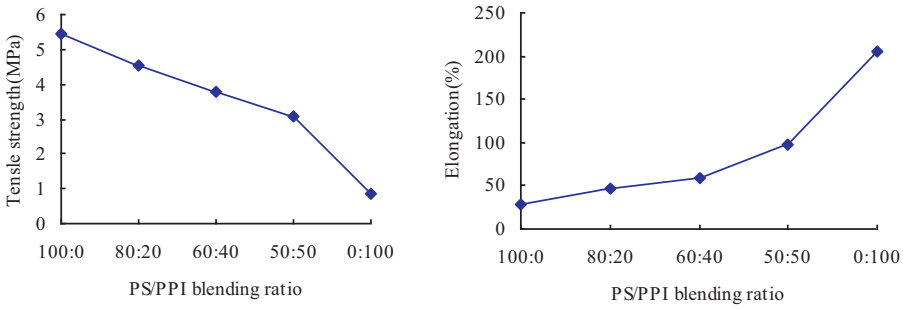


**Fig. 1.** Mechanical properties of the PS/PPI composite films.

ordered structure held together by intermolecular hydrogen bonds that provide strength to the structure. Aguilera, Esteban, Benitez, Molla, and Martin-Cabrejas (2009) suggested that PS formed swelled starch granules during the gelatinization process without forming any type of covalently integrated network to collect and hold the swollen granules together, making its structure much brittle and resulting the lower elongation of 100% PS films. The higher elongation of the PPI film may be related to the capability of the PPI to form an integrated network. Mehyar et al. (2012) found that whey protein isolate formed the dense network consisted of strong hydrostatic interactions and intermolecular disulfide bonds.

The addition of PPI to the PS film significantly reduced tensile strength from 5.44 MPa to 3.06 MPa but increased elongation from 28.56% to 98.12% when the PPI added ratio ranged from 0 to 50%. The decreased tensile strength and increased elongation of the PS/PPI blend films might be attributed to the interaction between the swollen PS granules and PPI, which led to the formation of a flexible network since our early results of SEM images of PS/PPI blends gel showed that the native PS gel without PPI showed a relatively dense and compact structure with some pores while the PS/PPI blends gels exhibited more pores and showed a honeycomb feature which indicated that PPI molecules can interact and modulate the structure of PS gel. The results in this study was in line with Chinma et al. (2012) who reported that addition of soy protein concentrate decreased the tensile strength of cassava starch film because of the fact that the higher protein content in film-forming solution, the higher the aggregation of protein that improved the film strength. According to Al-Hassan and Norziah (2012), the tensile strength of the sago film decreased with the increasing addition ratio of fish gelatin in sago starch solutions, as a result of the interaction between hydroxyl groups between starch and protein that may reduce the interaction between starch chains. Tapia-Blácido, Mauri, Menegalli, Sobral, and Anon (2007) suggested that the presence of proteins had significant effects on the mechanical properties of flour films, as protein evidently interfered with the formation of the starch network, conferring greater plasticity on the entire network.

Mechanical properties of films were characterized by TS and E values and high values were generally required. The results in this study indicated that PPI could be used to greatly improve the process ability with small decreases of TS of films.

### 3.3. The barrier properties of PS/PPI blend films

The barrier properties of films prepared from PS/PPI blends are shown in Table 3. 100% PS film had the highest film solubility, water vapor permeability (WVP) and water-vapor transmission rate (WVTR) than other films. The 100% PPI film had higher film solubility value (16.48%) than PS/PPI blend films. Film solubility value decreased from 22.31% to 9.78% upon the incorporation of PPI into PS at different levels.

The decrease in film solubility of PS films with increase in PPI ratio could be attributed to the interaction between PS and PPI, which indicated that PPI/PS blend films had good water stability than 100% PS film. During the process of gelatinization, more hydroxyls of PS were exposed and interacted with the free sulfidryl (SH) groups of PPI intermoleculars. Mohammed, Hill, and Mitchell (2000) suggested that a heating process can alter the three-dimensional structure of proteins and reveal the free SH groups and hydrophobic side chains. The film solubility resulted in this study was in line with that of Chinma et al. (2012). Bourtoom and Chinnan (2008) reported that the addition of chitosan to rice starch films resulted in a decrease in film solubility values, which could arise from the fact that higher chitosan content induced a rice starch and chitosan interaction and led to a decrease in the film solubility.

The decreases in film solubility, WVP and WVTR of PS film with the addition of PPI into PS solutions could be attributed to the changes in the functionality properties of the PS/PPI blends since the results of the water absorption capacity (WAC) and swelling power (SP) of PS/PPI blends in our early experiment showed that both WAC and SP decreased at 90 °C as the ratio of PPI in blends increased, which may improve the water resistance of blend films in this work.

Addition of 40% PPI to PS starch film significantly decreased WVP (from 11.18% to 4.19%) and WVTR (from 6.16% to 1.95%). According to Garcia, Martino, and Zaritzky (2000a), many factors, such as polymeric chain mobility and specific interaction between the functional groups of the polymers, had effects on WVP. The decreases of WVP and WVTR may be due to the formation of smooth and compact structure between PPI and PS, which inhibited the penetration of water into the PS matrix. Pranoto, Lee, and Park (2007) reported that the incorporation of gellan to gelatin films significantly reduced the WVP that may due to the ionic interaction between gelatin and gellan that formed a denser polymeric matrix.

The study of edible films permeability properties was used to show its influence on products performance and consumer acceptance. Since the incorporation of PPI into PS film could enhance the

**Table 3**
The barrier properties of PS/PPI blend films.

| Sample | Solubility (%) | WVP (g mm/m$^2$ h Pa) | WVTR (g/m$^2$ h) |
|---|---|---|---|
| $F_{100:0}$ | 22.31 ± 0.50$^a$ | 11.18 ± 0.16$^a$ | 6.16 ± 0.11$^a$ |
| $F_{80:20}$ | 18.33 ± 0.17$^b$ | 10.57 ± 0.08$^b$ | 5.42 ± 0.05$^c$ |
| $F_{60:40}$ | 12.49 ± 0.28$^d$ | 4.19 ± 0.04$^c$ | 1.95 ± 0.09$^d$ |
| $F_{50:50}$ | 9.78 ± 0.12$^e$ | 6.93 ± 0.09$^d$ | 3.13 ± 0.05$^e$ |
| $F_{0:100}$ | 16.48 ± 0.08$^c$ | 5.39 ± 0.19$^e$ | 4.85 ± 0.16$^b$ |

$F_{100:0}$, $F_{80:20}$, $F_{60:40}$, $F_{50:50}$ and $F_{0:100}$ means the mixed ratio of PS/PPI on a dry basis were 100:0, 80:20, 60:40, 50:50 and 0:100, respectively; WVP, water vapor permeability; WVTR, Water-vapor transmission rate.
Within the same columns, values with different superscripts letters (a, b, c, d and e) differ ($P < 0.05$).

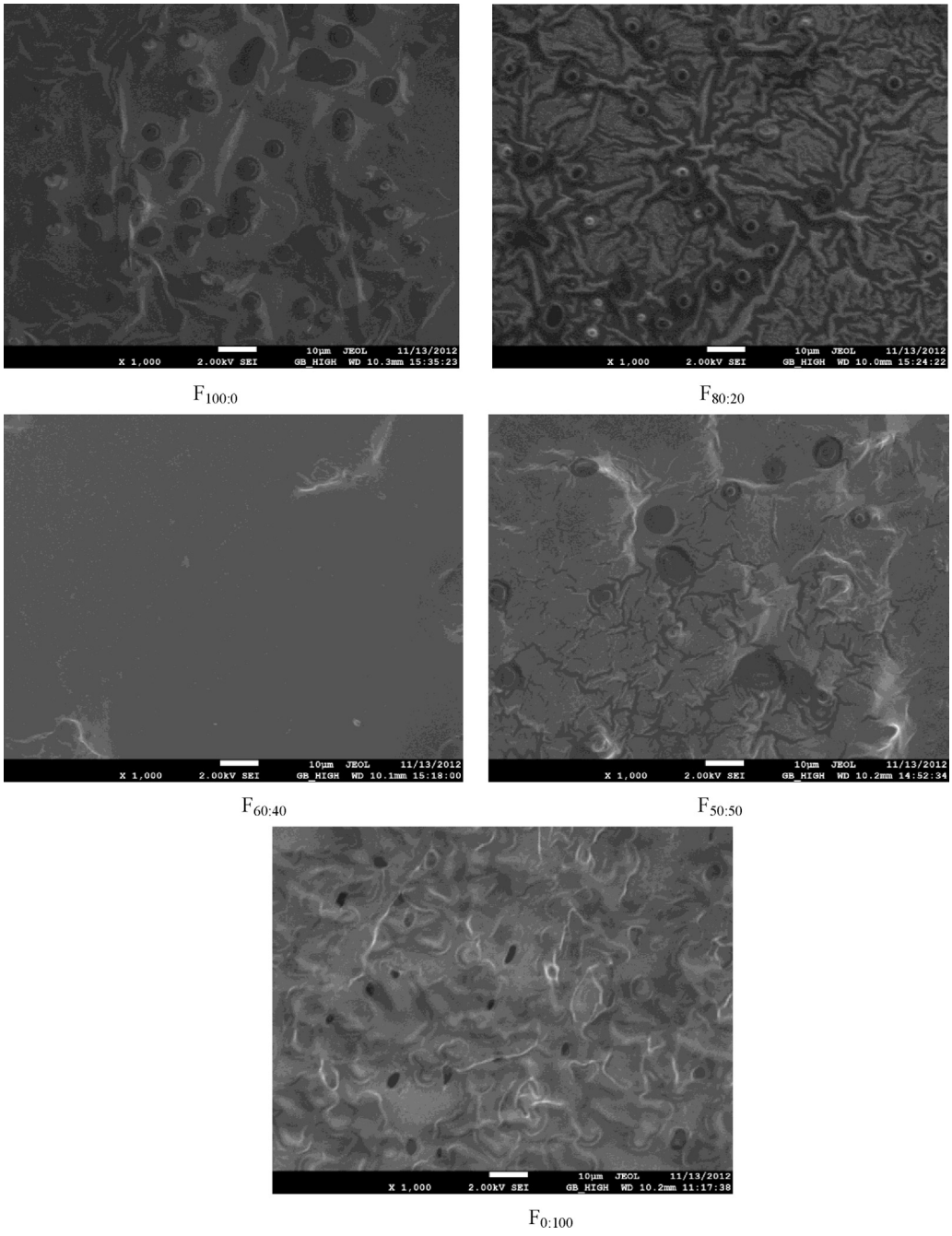


**Fig. 2.** SEM image of the surface of PS/PPI blend films. $F_{100:0}$, $F_{80:20}$, $F_{60:40}$, $F_{50:50}$ and $F_{0:100}$ means the mixed ratio of PS/PPI on a dry basis were 100:0, 80:20, 60:40, 50:50 and 0:100, respectively.

water stability properties but also decreased the WVP and WVTR, the obtained results in this work may be applied to the development of environmentally friend coatings for fresh fruits or films for food packages to enhance shelf life of food products.

### 3.4. SEM image of the surface of PS/PPI blend films

Fig. 2 shows the SEM photographs of PS/PPI blend films plasticized with glycerol. It was observed that there were some differences in surface of films at various PPI to PS ratios.

Many swollen starch granules were presented in the 100% PS film, which means only a part of the starch polymers was gelatinized completely. The result in this study was in line with Zhang and Han (2006a, 2006b) who reported that the commonly used methods (boiling and stirring starch solution at around 100 °C) to produce starch films are not good enough to solubilize starch polymers completely.

100% PPI film was observed to have rougher surfaces with presence of pores or cavities. The PS/PPI blend films upon the incorporation of PPI at 20% and 50% level were not homogeneous, indicating that low or more addition of PPI into PS film may disrupt the formation of PS gel network and caused phase separation. Mariani et al. (2009) reported that the addition of corn starch alone or starch with soy protein isolate, in different concentrations, decreased the homogeneous phase of pristine poly (3-caprolactone). However, the smoother film surface was

observed in PS/PPI blend films with the addition of PPI at 40% level, suggesting a homogeneous distribution of PPI in the PS matrix without apparent starch granules. The result may be due to the entanglement and intermolecular interactions between PPI and PS. Wang, Marcone, Barbut, and Lim (2012) found that the fractured surface of soy protein isolate film with incorporated anthocyanin-rich red raspberry (AARE) also demonstrated a smooth fractured surface structure, which suggested compatibility between the AARE and SPI. Ibarguren, Vivas, Bertuzzi, Apella, and Audisio (2010) reported that the microstructure of the wheat gluten, gelatin and brea gum films made with and without enterocin was homogeneous and compact (without pores).

### 3.5. SEM image of the cross-section of PS/PPI blend films

Cross sections of the obtained films are presented in Fig. 3. The 100% PS film showed a relative uniform and compact matrix without disruption and pore formation, indicating the integrity of the structure with strong strength. This result was in consistent with Mali and Grossmann (2002), who reported that compact and homogeneous matrix was observed by in yam starch-based films with glycerol produced by casting. The 100% PPI film displayed a smooth structure, which may be due to an enhanced gel formation by thiol/disulfide interchange reaction. The homogeneous matrix is a good indicator of high elongation as shown in Fig. 1.

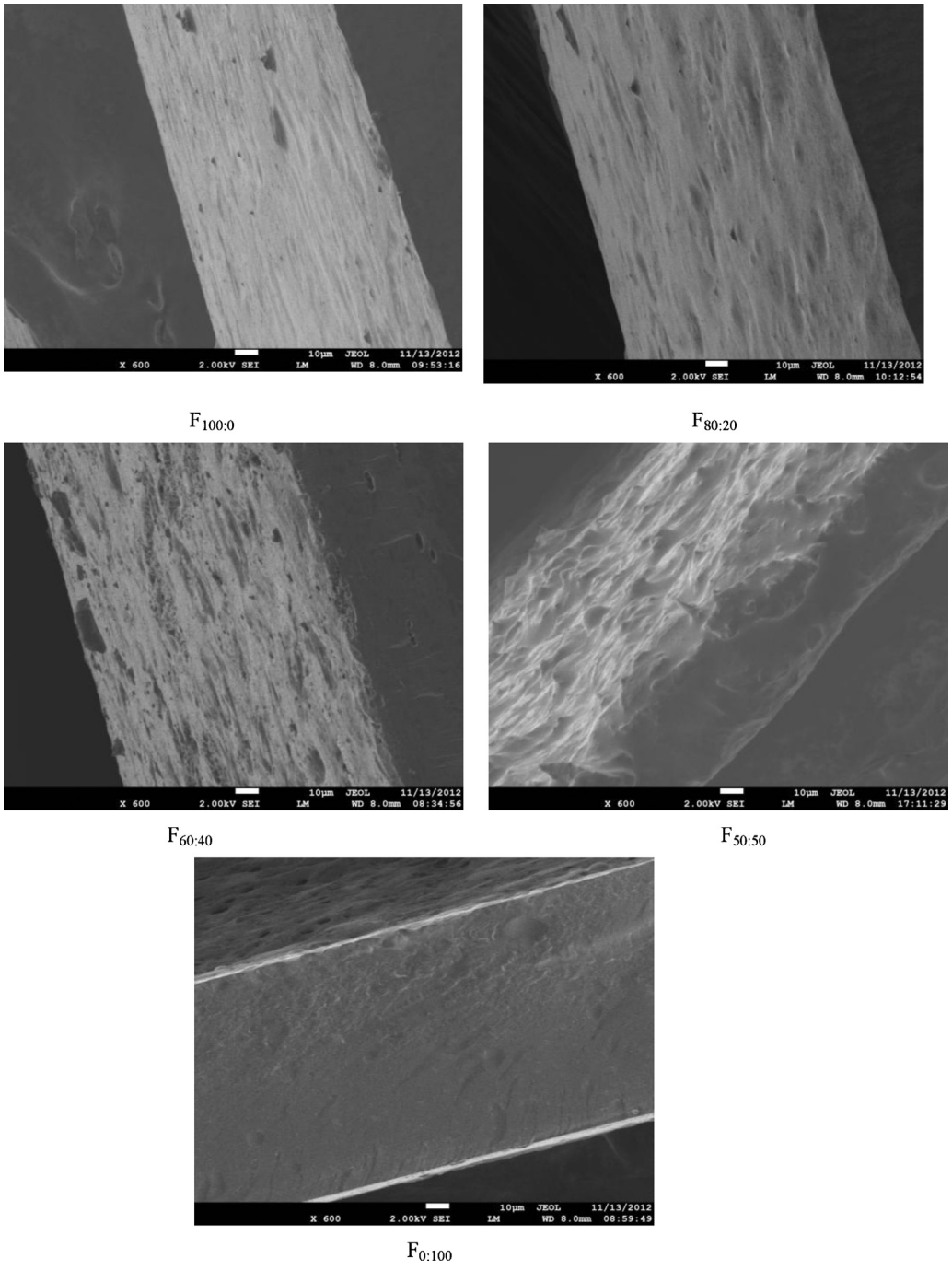


**Fig. 3.** SEM image of the cross-sections of the films.

No significant differences of cross-sections were observed when PPI was added into PS film at 20% level, which may be attributed to small addition of PPI. Therefore, small changes of mechanical properties would be expected, as were obtained in the mechanical tests. Rougher and flexible network was shown in blend film with the addition of PPI reaching 40% level. Uneven structure was presented in PS/PPI blend film upon the incorporation of PPI at 50% level. The results indicated that the high concentration of PPI in the PS film could interrupt the formation of starch network. During the gelatinization of the starch granules, the released amylose and amylopectin molecules interacted mainly through hydrogen bonds. The existence of PPI disturbed the formation of double helices of amylose with amylopectin branches, and then reduced the interaction between amylose and amylopectin molecules making the starch film flexible. According to Liu and Han (2005), the interactions between the amylose and amylopectin molecules contributed to the film formation, but were so strong that the starch films were readily brittle and rigid.

## 4. Conclusions

The elongation of PS film increased from 28.56% to 98.12% but tensile strength decreased from 5.44 MPa to 3.06 MPa with the incorporation of PPI into PS at 50% level, indicating that PPI could be used to greatly improve film flexibility with small decreases of TS of films. When PPI was added into PS film at 40% level, the WVP and WVTR of the films significantly decreased from 11.18% to 4.19% and 6.16% to 1.95%, respectively. The result showed that the water barrier properties of PS film were obviously improved by incorporation with PPI into PS solution at certain level, suggesting that the smooth and compact structure between PPI and PS was formed, which can be confirmed by SEM image of surface of PS/PPI blend film. Combining PPI and PS would be an attractive method to develop new edible films. It was observed from this work that the incorporation of PPI at 40% level into PS film may be the best option for desirable properties of edible films.

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