Chitosan/kudzu starch/ascorbic acid films: Rheological, wetting, release, and antibacterial properties

Xiaoyong Song¹* and Luming Cheng²

¹North China University of Water Resources and Electric Power 36 Beihuan Road Zhengzhou, P. R. 450011 China.
²The Second Hospital Affiliated to Zhengzhou University, Zhengzhou 450014, China.

Received 25 February, 2014; Accepted 7 November, 2014

Chitosan was blended with kudzu starch to prepare edible composite films adding ascorbic acid as antioxidant and Tween 20 as surfactant, and choosing acetic acid, lactic acid and malic acid as solvents. Rheology and wettability of film forming solutions, and antibacterial, release and physical properties of the composite films were investigated. Results showed that, acid solvent types significantly affected the rheology of film forming solutions but hardly had influence on wettability. The growth of *Escherichia coli* and *Staphylococcus aureus* were inhibited by the composite films, and the release process of ascorbic acid were effectively delayed. Among the composite films, film prepared by acetic acid had the strongest mechanical strength and the best controlled-release effect. Film choosing lactic acid as solvent had the best flexibility. The water vapor permeability coefficients of film using malic acid to dissolve was the smallest, and its antibacterial ability was the highest.

Key words: Chitosan/kudzu starch/ascorbic acid edible film, rheological properties, wettability, antibacterial properties, release behaviors, physical properties.

INTRODUCTION

In recent years, more attention has been paid to biopolymer-based edible food packaging as a potential alternative to synthetic polymer-based packaging materials which cause negative environmental impact due to their non-biodegradability.

Biopolymers, such as carbohydrates, proteins and lipids can fulfill the requirements for preparing edible films and these materials can be utilized individually or as mixed composite blends. These edible polymer films can totally cover food surfaces, form barriers against various small molecules including oxygen, moisture, aroma and oil, reduce mechanical injuries, and thus prevent food quality deterioration and preserve/improve food integrity (Siracusa et al., 2008). Besides, edible films can be chosen as carriers of many functional additives (such as antibacterials, antioxidants, flavors, and colorants) which enhance the functionality of the packaging materials (Martins et al., 2012). Nice edible films should be designed to meet a number of requirements, such as having proper mechanical properties, good appearances (adequate gloss and transparency) and favorable gas barrier properties (Pitak and Rakshit, 2011).

Among the biopolymers for formulating edible films, starch is one of the most promising raw materials owning to its biodegradability, abundance, low cost, renewability and film-forming ability (Averous et al., 2001;
Peressini et al., 2003). Furthermore, starch based films have been particularly considered because their physical properties are similar to synthetic polymers: transparent, tasteless, odorless, semi-permeable to CO2 and resistant to O2 passage (Nisperos-Carriedo, 1994; Skurtys and Dieulot, 2013; Woggum et al., 2014). Many researchers have studied the potential applications of starch edible films and confirmed their availability to extend the shelf life of fresh and minimal processed products (Bergo et al., 2008; Bertuzzi et al., 2007; Talja et al., 2007).

However, starch based films show several disadvantages, e.g. strong hydrophilic properties and inadequate mechanical characteristics (Chillo et al., 2008). In order to overcome the above shortcomings and improve the functional properties of starch films, blending with other biopolymers is a promising strategy (Flores et al., 2007; Gerschenson and Goyanes, 2009; Vásconez et al., 2009).

Chitosan is a natural polymer derived from deacetylation of chitin (Abuogch et al., 2011). Chitosan possesses immense potential as a packaging material in the food industry owing to its nontoxicity, biodegradability, biocompatibility, antimicrobial activity and film forming capacity (Abuogch et al., 2011). In addition, chitosan films have low oxygen permeability coefficients, good mechanical properties which insure their widely applications (Avila-Sosa et al., 2012; Bonilla et al., 2012). Some reports have indicated that starch and chitosan can form nice composite films which possess better properties than films using them alone (Bourtom and Chinnan, 2008; Vásconez et al., 2009). However, chitosan is only soluble in some acid solutions and acid types can significantly affect the behaviors of chitosan based films (Kim et al., 2006).

In addition, incorporating natural preservatives (such as antioxidant and antimicrobial materials) into edible films is an effective alternative to reduce the dosage of chemical preservation agent. These active additives that enhanced films can keep ensuring the safety of food surfaces through the controlled release of active substances (Devlieghere et al., 2004; Fatih et al., 2009), which display obvious advantages over the direct application of preserving agents, e.g. smaller agent dosage is needed to achieve a target shelf life. Ascorbic acid is one of the most extensively used additives as a dietary supplement of vitamin C and an antioxidant to protect the food quality (Bastos et al., 2009).

To the best of our knowledge, there is little comprehensive study of the effects of different acid-solvents on the rheology, and wettability of chitosan based film-forming-solutions (FFSs), in addition to the release behaviors of active additives from films. In this present paper, chitosan was blending with kudzu starch, a traditional healthy food in China to cast composite films choosing ascorbic acid as additive. The effects of three acid solvents (acetic acid, lactic acid, and malic acid) on the wettability and rheological properties of FFSs were studies, besides, the antibacterial, physical and controlled-release properties of edible films were also considered in order to provide useful knowledge of its possible applications in prolonging food shelf life.

MATERIALS AND METHODS

Kudzu starch (Pueraria lobata, water content: ca.14%, amylose: ca.30%) was purchased from Xichuan Chunya Geye Biotechnology Co., Ltd. (Hunan, China). Chitosan (molecular weight: ca. 420 kDa, deacetylated degree: 88.5%) was purchased from AK Biotech Ltd. (Shandong, China). Glycerol, ascorbic acid, acetic acid, lactic acid, DL-malic acid, anhydrous calcium chloride and sodium chloride were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Tween 20 (C_{18}H_{37}O_{14}Na) obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China) was used as surfactant to increase the wettability of the FFSs. Luria–Bertani broth (LB) and tryptone soy broth (TSB) were purchased from Qingdao Hope Bio-technology Co., Ltd. (Shandong, China). Escherichia coli CMCC44102 and Staphylococcus aureus ATCC6538 were kindly provided by the lab of department of Food Science and Technology, Shanghai Jiao Tong University (Shanghai, China).

Film preparation

Kudzu starch was dispersed in deionized water to obtain 2% (w/v) kudzu suspension. The solution was heated at about 100°C for 15 min under stirring to accomplish a complete starch gelatinization, during the process glyceroxel (0.6%, w/v) and tween 20 (0.1%, w/v) were added. 2% (w/v) of chitosan solution was prepared by dispersing chitosan in 1% (w/v) of acetic acid, lactic acid or malic acid solution and stirring with a magnetic stirrer (Shanghai Huxi analysis instrument factory Co., Ltd., Shanghai, China). In order to achieve more flexible films, glycerol (0.6%, w/v) and tween 20 (0.1%, w/v) were added. After chitosan was dissolved completely, the solution was filtered with cheesecloth.

Chitosan/kudzu suspensions were prepared by mixing 100 ml of chitosan solution and 100 ml of suspension together. All the solutions were cooled to room temperature and adjusted to pH = 4.0 with corresponding acid (Vásconez et al., 2009). Then, 0.5% (w/v) of ascorbic acid was added and the solutions were stirred for 5 min, and pH was measured, adjusted and measured again. After homogeneous processing, the FFSs were transferred into a vacuum oven for about 1 h at room temperature to remove the air bubbles.

About 200 ml of solutions were casted over the leveled glass plates (25 × 25 cm) and dried at room temperature for at least 16 h until the weights approached to constant values giving films with ca. 0.1 mm thickness. Thereafter, the films were carefully peeled from the plates and stored for 48 h in a constant temperature and humidity chamber (KBFT720, Binder, Germany) at 50% relative humidity and 25°C before further tests. Chitosan/kudzu starch/ascorbic acid composite film (solution) was recorded as Ch-Ku-As. The composite film (solution) as chitosan dissolved in acetic acid, lactic acid, and malic acid were recorded as Ch-Ku(Aa)-As, Ch-Ku(La)-As and Ch-Ku(Ma)-As, respectively.

Contact angle

The measurement of the contact angles of FFSs on the clean leveled surface of sized glass and paraffin wax substrates were performed using a Contact Angle Analyzer (DSA 30, Kruss Co., Germany) at room temperature. Six replicate determinations were carried out for each sample, and the results were averaged.
**Rheological measurements**

Rheological tests of degassed FFSs were performed by a controlled-stress rheometer (Brookfield R/S–CC, Brookfield Engineering Laboratories, Inc., Massachusetts, USA) using CC25 coaxial cylinder sensor. The measurements were conducted at 25 ± 0.5°C controlled by circulating water. For steady-shear measurements, all the samples were sheared continuously at shear rates ranging from 0 to 1000 s\(^{-1}\), using 10 min to reach the maximum shear rate and another 10 min back to zero shear rate. The apparent viscosity was recorded as a function of shear rate. The Ostwald de Waele model (Equation 1) was applied to determine the consistency index and flow-behavior index, a dimensionless number that indicates the closeness to Newtonian flow. It takes a value of 1 for Newtonian, between 0 and 1 for pseudoplastic fluids and higher than 1 for dilatant fluids (Xiao et al., 2012).

\[
\sigma = k \cdot \gamma^n
\]  

Where \(\sigma\) is the shear stress (Pa), \(\gamma\) is the shear rate (s\(^{-1}\)), \(k\) is the consistency index (Pa s \(n\)), and \(n\) is the dimensionless flow behavior index.

**Antibacterial tests**

Antibacterial tests of Ch-Ku-As films were conducted by liquid culture method (Bajpai et al., 2010), with *E. coli* and *S. aureus* as model bacteria. All the solutions and vessels used were sterilized before tests. The tests were conducted under sterile conditions and were run in triplicates. A loop of *E. coli* was inoculated into 25 ml LB whereas a loop of *S. aureus* was inoculated into 25 ml TSB, respectively. The bacteria suspensions were then incubated in a constant temperature vibrator (Taicang Experimental Equipment Plant, Jiangsu, China) with a shaking speed of 200 rpm at 37°C overnight. In order to display the inhibitory differences of Ch-Ku-As films more clearly, appropriate amounts of the overnight bacterial cell suspensions and 1.25 g (dry weight) of the Ch-Ku-As films were mixed more clearly, appropriate amounts of the overnight suspensions were again transferred into sterilized nutrient broths and incubated at 37°C to the exponential growth phase for 16 h. *E. coli* and *S. aureus* suspensions were 5 × 10\(^8\) CFU/ml, respectively. The bacteria suspensions were then incubated in a constant temperature oscillator (Taicang Experimental Equipment Plant, Jiangsu, China) with a shaking speed of 200 rpm at 37°C. Suspension-aliquots were taken out every 15 min during experiment and measured the optical density (OD) at 600 nm to reflect the bacteria growth using a UV–2100 spectrophotometer (UNICO (Shanghai) Instruments Co., Ltd., Shanghai, China) until 90 min.

**Release test**

Release test was carried out based on the method described by Flores et al. (2007) with some modifications. Film discs (\(\Phi = 1.4\) cm) were put into weighing bottles (\(\Phi 70 \times 35\) mm) containing 60 ml of distilled water and stirred magnetically at 150 rpm. The contents of ascorbic acid released to water during experiment was determined by the antioxidant activities in water which were monitored by taking 1 mL of samples at different time periods (1, 3, 5, 7, 9, 15, 20, 25, 30, 45, and 60 min) at 25°C and using DPPH decolorization assay to calculate. The release test was done in triplicate for each film.

We used Fick’s second law to describe the release behavior of ascorbic acid (Mastromatteo et al., 2009).

\[
\frac{M_t}{M_w} = 1 - 8 \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[\frac{-(2n+1)^2D\tau}{L^2}\right]
\]  

Where \(M_t\) was the ascorbic acid concentration at time \(t\) (g ascorbic acid/g film), \(M_w\) was the equilibrium ascorbic acid concentration (g ascorbic acid/g film), \(L\) was the thickness of film (m), \(D\) was diffusion coefficient (m\(^2\)/s), \(\tau\) was releasing time (min), \(n\) was the positive integer.

**Water vapor permeability**

The water vapor permeability (WVP) of film was determined gravimetrically based on the ASTM E96-95 (ASTM, 1995a) method with some modifications. The film thickness was measured at five randomly chosen points using a digital micrometer (with an accuracy of 0.02 mm) before test and the mean value was used to calculate WVP. The films were sealed on the top of permeation cells (diameter 21 mm and height 25 mm) containing granular \(\Phi < 2\) mm anhydrous calcium chloride. The cells were placed in desicators containing saturated NaCl solutions at 25°C and provided 0/75% relative humidity gradient. The cells were weighed as a function of time until the steady state was reached using an analytical balance (±0.0001 g). WVP was calculated as follow:

\[
WVP = \frac{mL}{At \Delta P}
\]  

Where \(m\) is the weight of water permeated through the films (g), \(L\) is the average thickness of edible films (m), \(A\) is the permeation area (m\(^2\)), \(t\) is the time of permeation (s), and \(\Delta P\) is the partial water vapor pressure difference across the two sides of the film (Pa). Five replicates were obtained for each test.

**Mechanical properties**

Mechanical properties of films were determined according to the method described by Chen et al. (2010) with some modifications and were carried out using a texture analyzer (TA-XTplus, Stable Micro systems, Surrey, UK) at room temperature. Eight repetitions were performed for each sample. During the test, rectangular films of 20 × 80 mm were mounted between the tensile grips (A/TG model) and stretched at a rate of 0.8 mm s\(^{-1}\) until breaking. Initial grip separation was set at 50 mm. Tensile strength (TS, MPa) and elongation at break (EAB, %) were determined from stress-strain curves obtained from force-deformation data.

**Color**

Film disks with 40 mm diameter were used for color measurement by a Color Difference Meter (WSC-S, Shanghai Precise Scientific Apparatus, Shanghai, China). CIE-Lab coordinates were obtained from the reflection spectra of the samples using a D65 illuminant. The exposed area was sufficiently greater in relation to the illuminated area to avoid any edge effect. The Hunterlab parameters: \(L, a,\) and \(b\) were measured according to a standard test method (ASTM, 1995b). At least five positions were randomly selected for each sample. Color parameters ranged from black \((L = 0)\) to white \((L = 100)\); greenness \((-a)\) to redness \((+a)\); and blueness \((-b)\) to yellowness \((+b)\).
Table 1. Properties of Ch-Ku-As film-forming solutions.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Contact angle (°)a,b</th>
<th>Non-Newtonian index (n)</th>
<th>Consistency coefficient (K)</th>
<th>Correlation coefficient (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>On glass</td>
<td>On paraffin wax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch-Ku(Aa)-As</td>
<td>27.8 ± 1.2²</td>
<td>85.7 ± 1.7²</td>
<td>0.8150</td>
<td>0.3128</td>
</tr>
<tr>
<td>Ch-Ku(La)-As</td>
<td>27.8 ± 2.2²</td>
<td>83.4 ± 5.1²</td>
<td>0.8337</td>
<td>0.2702</td>
</tr>
<tr>
<td>Ch-Ku(Ma)-As</td>
<td>27.0 ± 0.4²</td>
<td>82.9 ± 1.3²</td>
<td>0.9585</td>
<td>0.1127</td>
</tr>
</tbody>
</table>

a Data were shown in values ± standard deviation (n=6). b Different superscript letters in the same column indicated significant differences (P < 0.05).

RESULTS AND DISCUSSION

Contact angle

Contact angle is usually the angle of liquid where a liquid/vapor interface meets a solid surface, and its value is mainly affected by both of the droplet’s inherent properties and the liquid-solid interaction. Contact angle of FFS reflects its wetting behavior on food surface, subsequently affects its adhesion ability. In the paper, glass was chosen as hydrophilic solid and paraffin wax was chosen as hydrophobic solid in order to simulate the wetting behaviors of FFSs on different polar solid surfaces. The static contact angles of FFSs were measured by sessile drop technique.

It was found in Table 1 that the contact angle values of FFSs on glass substrates were all small, indicating the solutions were easy to spread on a hydrophilic substrate. When FFSs were dropped on the surfaces of paraffin wax, the hydrophobic groups of the surfactants preferred to interact with wax, whereas the hydrophilic groups tended to access to solutions. That is, the amount of surfactant adsorbed by the solid surface increases with increasing the concentration of the active agent, and consequently the interface tension between solid and liquid is reduced and contact angle decreases. When the concentration reaches or exceeds a critical value, the adsorption amount is no longer increasing, and the interface tension and contact angle hardly change. A literature showed that the critical micelle concentration of tween 20 is less than 0.01% (Garstecki et al., 2005). In this experiment, the concentration of tween 20 was 0.1%, so we could consider that the contact angles of FFSs on paraffin wax surfaces have reached to the lowest values. Besides, the contact angle values of FFSs on paraffin wax substrate were all less than 90°, lower than those of normal starch FFSs (Xu et al., 2005). However, the contact angle values did not show significant differences among FFSs prepared by three acids (P > 0.05), which indicated that acid types did not obviously affect the wettability of FFSs.

Rheological measurement

The rheological curves of FFSs were shown in Figure 1. The results displayed that, at the same shearing rate, the sequence of apparent viscosity was Ch-Ku(Aa)-As ≥ Ch-Ku(La)-As > Ch-Ku(Ma)-As. Apparent viscosity of a polymer solution at a given shearing rate is mainly determined by the free volume of the fluid and the entanglements among macromolecules. The free volume refers to the space not occupied by atoms, where the diffusion of macromolecular chain segments mainly occurs. If the free volume decreases, the space of molecular motion will reduce, and thus the viscosity of polymer fluid will increase. Moreover, certain numbers of intermolecular-entanglements are retained after the dissolution of polymer. Greater molecular weight and longer molecular chain will result in greater density of the entangled points, higher resistance of the molecular movement, and thus larger viscosity of polymer fluid. According to previous research, chitosan forms more dimers in acetic acid solution than in other acid solutions, which suggests more compact structures of FFS than those prepared with other acid solutions (Park et al., 2002). From Figure 1, we can also find that FFSs belong to pseudoplastic fluid. The apparent viscosity of Ch-Ku(Aa)-As and Ch-Ku(La)-As dropped substantially with the increase of shearing rate, while the change range of Ch-Ku(Ma)-As was small at different shear rates. The smaller changes of viscosity for Ch-Ku(Ma)-As may be attributed to the strong acidity of malic acid, which produced smaller numbers of macromolecules tangles. Therefore, shear rate had little effect on its apparent viscosity. In
addition, the lag area of Ch-Ku(Aa)-As and Ch-Ku(La)-As was relatively similar, and the Ch-Ku(Ma)-As hardly showed hysteresis loop. This phenomenon indicated that when the solutions were subjected to shear, Ch-Ku(Ma)-As was more likely to return to the initial state compared with the other two FFSs.

We can calculate the parameters of rheological properties by fitting lnγ versus lnτ. As observed in Table 1, the non-Newtonian indexes of Ch-Ku(Aa)-As, Ch-Ku(La)-As and Ch-Ku(Ma)-As were 0.8150, 0.8337, and 0.9585, respectively. Results showed that the pseudoplastic decreased, Newtonian increased, and consistency reduced following the sequence of Ch-Ku(Aa)-As, Ch-Ku(La)-As and Ch-Ku(Ma)-As.

**Antibacterial tests**

Results of antibacterial experiment were presented in Figure 2. As for *E. coli*, it was quite clear that OD values of the control assay increased consistently during the test indicated an appreciable growth of the bacteria, but the OD values were suppressed greatly in suspensions containing Ch-Ku-As films.

After treated with Ch-Ku(Aa)-As film for 30 min, the OD values of the bacteria suspensions were significantly lower than in the control group (*P* < 0.05). However, 15 min after adding Ch-Ku(La)-As and Ch-Ku(Ma)-As films, the growth of *E. coli* can be effectively inhibited. Figure 2B showed that *S. aureus* kept growing in each experimental group throughout the whole stage, but the Ch-Ku-As films significantly inhibited (*P* < 0.05) the growth trends of bacteria.

Ascorbic acid and surfactant can improve the antibacterial ability of edible packaging film (Bastos et al., 2009). For ascorbic acid, on the one hand it can enhance the acidity of the solution and deteriorate the bacterial growth environment; on the other hand, the rapid reaction between ascorbic acid and oxygen hinders the oxygen source for aerobic bacteria (Tajkarimi and Ibrahim, 2011).

The reason why surfactant enhances antibacterial ability of the composite films is mainly due to its special
molecular structure. The format of chitosan in acidic solution is usually the aggregation of several molecular chains. When surfactant is added, the amino or hydroxyl groups of chitosan can interact with the hydrophilic groups of the surfactant, forming dynamic association bodies; at the meantime, long hydrophobic alkyl-chains can induce chitosan to depolymerized into single strands and stretch the chain conformations. Compared with the aggregates, although the numbers of total amino groups did not change, more protonated amino groups were exposed when chitosan in single chain format. Consequently, the numbers of positively charged amino groups in contact with the bacterial cells increased. In addition, the long alkyl-chains of surfactant tended to infiltrate into the internal hydrophobic membranes of the bacteria due to the hydrophobic interaction, making the interactions between chitosan and bacterial cells more easily, and more effectively interrupting the normal functions of the bacteria membranes.

**Release test**

According to the release data, the release process of ascorbic acid was generally divided into three stages (Figure 3):

1) Rapid release stage: In this stage, about 50 to 90% of
the total ascorbic acid fast released to water, caused by the rapid release of the ascorbic acid adsorbed on the film surface.

2) Slow release stage: The amount of released ascorbic acid accounted for 5 to 30% of the total content, which attribute to its slow release from the inside of the composite film.

3) Balance release stage: In this stage, the concentration of ascorbic acid changed very little.

Table 2 presented that the diffusion coefficient (D) of ascorbic acid from Ch-Ku(Aa)-As film was $0.24 \times 10^{-11}$ m$^2$ s$^{-1}$, significantly smaller than the values of the other two films ($P < 0.05$), which was 27.9 and 23.5% for Ch-Ku(La)-As and Ch-Ku(Ma)-As film, respectively.

As for Ch-Ku(Aa)-As film, ascorbic acid release was mainly controlled by the film swelling process. At initial stage, the ascorbic acid molecules in direct contact with water were quickly dissolved. Subsequently, water molecule penetrated into Ch-Ku(Aa)-As network and ascorbic acid gradually diffused into water through the channel formed by swelling. As time goes by, Ch-Ku(Aa)-As film achieved maximum swelling degree and the release of ascorbic acid achieved a dynamic balancing process.

Compared with Ch-Ku(Aa)-As film, Ch-Ku(La)-As and Ch-Ku(Ma)-As films had weak sustained-release effect on ascorbic acid, and the diffusion badly followed Fick’s second law. The reason may be that during the test, film erosion kept going for these two films and the network structures of the films were destroyed. Consequently, ascorbic acid from inner films could be quickly released to water, causing faster release speed.

### Water vapor permeability and mechanical properties

Mechanical property reflects the film’s ability to protect the physical integrity of foods (Martins et al., 2012). Table 2 showed that Ch-Ku(Aa)-As had the strongest mechanical strength, the average tensile strength was 5.73 MPa. Ch-Ku(La)-As film had the best flexibility, its average elongation at break was 71.51%. The mechanical properties of Ch-Ku(Ma)-As films were between those of the former films. It has been reported, the molecular structures of chitosan dissolved in different solvents varied due to different peculiarities of acid solutions, which in turn influenced the mechanical properties of the resulting films. Similar phenomena were also found by other researchers (Kim et al., 2006).

The water vapor permeability coefficients of Ch-Ku-As films were presented in Table 2. In this paper, the average WVP coefficients of Ku-Ch(Ma)-As film was ca. 27% lower than that of Ku-Ch(Aa)-As film and ca. 40% lower than that of Ku-Ch(La)-As film. The sequences of WVP coefficients were consistent with those in surface wettability test. Adding ascorbic acid could enhance the hydrophilic nature of edible packaging film (Bastos et al., 2009), whereas the hydrophobic interactions between the surfactant (tween 20) and the film-forming components...
Table 2. Diffusion coefficients (D), mechanical properties and WVP values of Ch-Ku-As films $^{a,b}$.

<table>
<thead>
<tr>
<th>Film</th>
<th>TS (MPa)</th>
<th>EAB (%)</th>
<th>WVP ($\times 10^{-11}$gm–1s–1 Pa–1)</th>
<th>D ($\times 10^{-11}$m2s–1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch-Ku(Aa)-As</td>
<td>5.73 ± 0.81$^a$</td>
<td>58.07 ± 5.60$^c$</td>
<td>6.64 ± 0.46$^b$</td>
<td>0.24 ± 0.01$^b$</td>
</tr>
<tr>
<td>Ch-Ku(La)-As</td>
<td>2.53 ± 0.26$^c$</td>
<td>71.51 ± 4.37$^a$</td>
<td>8.10 ± 0.68$^a$</td>
<td>0.86 ± 0.11$^a$</td>
</tr>
<tr>
<td>Ch-Ku(Ma)-As</td>
<td>3.60 ± 0.39$^b$</td>
<td>65.52 ± 2.31$^b$</td>
<td>4.82 ± 0.40$^c$</td>
<td>1.02 ± 0.11$^a$</td>
</tr>
</tbody>
</table>

$^a$ Results of TS, EAB, and WVP are the mean values ± standard deviation (n=8); Results of diffusion coefficient are the mean values ± standard deviation (for TS, EAB, and WVP, n=8; for D, n=3). $^b$ Different letters in the same column indicate significant differences ($P < 0.05$).

Table 3. Color analysis of Ch-Ku-As films $^{a,b}$.

<table>
<thead>
<tr>
<th>Film</th>
<th>$L$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch-Ku(Aa)-As</td>
<td>66.52 ± 0.45$^a$</td>
<td>19.33 ± 0.54$^b$</td>
<td>50.66 ± 0.81$^a$</td>
</tr>
<tr>
<td>Ch-Ku(La)-As</td>
<td>62.17 ± 0.39$^c$</td>
<td>22.58 ± 0.46$^a$</td>
<td>52.12 ± 1.32$^a$</td>
</tr>
<tr>
<td>Ch-Ku(Ma)-As</td>
<td>64.83 ± 0.34$^b$</td>
<td>18.44 ± 1.24$^b$</td>
<td>48.77 ± 1.01$^b$</td>
</tr>
</tbody>
</table>

$^a$ Results are the mean values ± standard deviation (n=8). $^b$ Different letters in the same column indicate significant differences ($P < 0.05$).

helped to produce better water blocking performance, which resulted in lower WVP values of Ch-Ku-As films than those of other chitosan-starch composite films (Xu et al., 2013).

Color

The color parameters of Ch-Ku-As film were shown in Table 3. The color values of Ch-Ku-As films were lower than general chitosan-starch composite films represented by lower $L$ values, and higher $a$ and $b$ parameters (Choi et al., 2002). Literature described that, the browning of ascorbic acid could easily occur in atmosphere due to its oxidization, and at meanwhile, it could react with free amino acids in chitosan to produce red and yellow pigments (Choi et al., 2002). From Table 3, we also found that ascorbic acid had the most significant influence on Ch-Ku(La)-As film, leading to the minimum brightness and the maximum redness and yellowness.

Conclusions

According to the results obtained in this study, chitosan and kudzu starch could be readily blended to form new edible biocomposite films. The FFSs prepared by three acid solvents belonged to pseudoplastic fluids. According to the sequence of acetic, lactic and malic acid, the pseudoplastic of FFSs reduced, Newtonian behavior enhanced, and consistency increased. The wettability of FFSs on glass substrate was better than that on paraffin wax substrate and not obviously effected by acid solvents. The composite films had significant inhibitory action on the growth of $E.\ col i$ and $S.\ aureus$, especially for Ch-Ku(Ma)-As films. In addition, the release of ascorbic acid was effectively delayed by composite films. The release of acetic acid from Ch-Ku(Aa)-As film was mainly influenced by swelling action, and in other two films were controlled by the film corrosion as well. Among the three composite films, Ch-Ku(Aa)-As film had the strongest mechanical strength, Ch-Ku(La)-As film showed the best flexibility, and Ch-Ku(Ma)-As film possessed the strongest antibacterial and water vapor barrier ability. The results suggested that this kind of composite films had potentially application in food industry.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGEMENTS

This research was funded by the National Natural Science Foundation of China (31301586), the Key Project of Education Department Henan Province (13A210729), the Youth science and technology innovation talents support program of North China University of Water Resources and Electric Power.

REFERENCES


American society for testing materials, West Conshohocken, PA, USA.