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Effects of corn fiber gum (CFG) on the pasting and thermal behaviors of maize starch

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ABSTRACT

Corn fiber gum (CFG) was a novel arabinoxylan hydrocolloid and recent researches showed its considerable potential in food processing. In this study, the interactions of maize starch and CFG were studied. Maize starch/CFG blend gels were prepared from maize starch suspension mixing with 0.1%, 0.25%, 0.5%, 1.0% (w/w) CFG. The pasting and thermal properties, rheological properties, microstructure, leached amylose and swelling power characteristics were evaluated. Compared with the reference, CFG addition lowered peak viscosity and breakdown of the composite system, but increased final viscosity in RVA measurement. The swelling power and the amount of leached amylose of maize starch gels were reduced as the addition concentration of CFG increased. The thermal characteristics of maize starch/CFG mixtures varied insignificantly as determined in DSC heating process. Rheological parameters, such as storage modulus (G') and loss modulus (G''), of the maize starches were observed to increase when CFG was present, supporting the hypothesis that the interaction between CFG and amylose could happen in the composite system. Confocal laser scanning microscopy (CLSM) confirmed changes in gels microstructure as starch components tended to be inhibited from leaching out of the granules when CFG was added, and the morphology of starch granule was more compact when CFG was added.

1. Introduction

Non-starch hydrocolloids were often used in starch-containing systems to improve quality and stability of final products since at least about 1950 (Krog, 1981; Chaisawang & Suphantharika, 2005; Nagano, Tamaki, & Funami, 2008), because polysaccharides exhibit many functional properties to control rheological and textural properties of starch-based foods. These hydrocolloids have the advantage of being extracted or derived from natural sources (Glicksman, 1992). From a nutritional point of view, most of them can be regarded as dietary fiber because they are only partially or not hydrolyzed by the enzymes in the human digestive tract (Izydorczyk & Dexter, 2008). The effects of various hydrocolloids addition on starch gels or pastes, such as xanthan gum, guar gum, gellan, carrageenan, or flaxseed gum have been studied extensively (BeMiller, 2011). Addition of certain hydrocolloid can also overcome the shortcomings of native starches without chemical modification. For example, hydrocolloids can protect starch granules against shear during pasting, modify product rheology (Kulicke, Eidam, Kath, Kix, & Kull, 1996), hold moisture (Yoshimura, Takaya, & Nishinari, 1996), and protect against syneresis (Alloncle and Doublier, 1991). Beside a series of studies on starch/galactomannan composite systems (Funami et al., 2005a), limited researches focused on the functions of arabinoxylan on starch gelling properties. Arabinoxylan is a hemicellulose mainly found in cereal grains, and it constitutes the major cell-wall polysaccharides of wheat and maize endosperm (Izydorczyk & Dexter, 2008). Gudmundsson, Eliasson, Bebgtsson, & Aman (1991) found that the arabinoxylan had a negligible effect on starch gelatinization and it decreased the water availability of the starch which thereby, increased the retrogradation degree. Biliaderis, Arvanitoyannis, Izydorczyk, & Prokopowich (1997) claimed that adding of arabinoxylan extended the gelatinization temperature range and the melting enthalpy of starch crystallites. Some studies have been done to elucidate the interaction between macromolecules which are governed by interactions between

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hydrocolloids molecules and amylose molecules (BeMiller, 2011; Funami et al., 2005b).

Corn fiber is accepted as an abundant low-valued byproduct of the corn dry and wet milling process today. Corn fiber gum (CFG) is an arabinoxylan (hemicellulose B) isolated from deoiled and destarched corn fiber by an alkaline hydrogen peroxide extraction process (Yadav, Fishman, Chau, Johnston, & Hicks, 2007a). CFG is a high molecular-weight hydrophilic biopolymer containing the following glycosyl composition: D-xylose (48–54%), L-arabinose (33–35%), galactose (7–11%), and glucuronic acid (3–6%) (Yadav et al., 2007a). It has a highly branched structure with a β-(1-4)-xylopyranose backbone and with α-L-arabinofuranose residues as side chains on both primary and secondary hydroxyl groups (Saulnier, Vigouroux, & Thibault, 1995). D-glucuronic acid residues are linked to the O-2 position of the xylose residue of the main bone (Montgomery & Smith, 1957) and galactose and some xylose residues attached to the arabinofuranosyl branches (Whistler & Corbett, 1955). CFG fractions often contain minor, actually functional amounts of protein (0.4–9% depending upon fiber source and isolation process), and up to 0.5% of various lipids, phenolics, and nutraceuticals such as phytosterols (the content of lipids is 0.24–0.43%) (Yadav, Moreau, & Hicks, 2007b). In recent years, research focuses on finding more valuable properties of CFG including adhesive, thickening and stabilizing, and film forming and emulsifying (Mikkonen et al., 2008; Woo, 2001). In addition, few studies have been conducted to examine the effect of CFG on the gelation process of starch gel when CFG was added as functional component in starch-based food system.

As Yadav et al. (2007a) claimed that CFG was a unique polysaccharide with low solution viscosity (the weight-average-intrinsic viscosity was between 1.35 and 1.71 dL/g) and high solubility, and it was proposed as an excellent emulsifier to stabilize beverage emulsion. Since ancient times in China, the starchy fruit and vegetable beverages are popular. These drinks are made of maize, lotus seed, edible lilium, etc. In our previous study, the thermal and microstructural properties of starch after mechanical treatment were researched (Qiu et al., 2014). The objectives of this work were to determine the effect of CFG on the gelling and rheological properties of maize starch. We studied starch-based system by using maize starch and CFG blend model, and enhanced the understanding of starch/arabinoxylan mixture system.

2. Materials and methods

2.1. Materials

Commercial native maize starch (11.6% (w/w) moisture; 0.35% (w/w) total lipid content, 0.18% (w/w) ash content; 26.6% (w/w) amylose content) was purchased from Beijing Haoshihui Food Corporation (Beijing, China). Laboratorial extraction of food-grade CFG was kindly provided by Eastern Regional Research Center, Agricultural Research Service, United States Department of Agriculture (USA).

2.2. Preparation of CFG solutions

Different concentrations of CFG solutions were prepared on 0.1, 0.25, 0.5, 1.0% (w/w) percentages on a dry basis using a magnetic stirrer (Shanghai Sile instrument Co., Ltd, S21-1, Shanghai, China) for 1 h at room temperature.

2.3. Pasting and paste properties

Pasting viscosity characteristics of starch/CFG mixtures were pasted using a Rapid Visco Analyzer (Newport Scientific Pty. Ltd., RVA-4, Sydney, Australia). Starch (1.4 g, dry basis) was added to an aluminum canister containing 0.1%, 0.25%, 0.5% and 1.0% (w/w) CFG or deionized water (as a control) to make a total weight of 28.0 g. The suspensions were kept 10 min at room temperature to equilibrate. The heating and cooling cycles of RVA were using "Standard method 2" thermal program offered by the supplier. The suspensions were held at 50 °C for 60 s, and then raised to 95 °C within 510 s. They were maintained at 95 °C for 300 s, cooled to 50 °C at the same scanning rate, and held at 50 °C for 120 s to develop the final paste viscosity. The rotation speed of the plastic paddle was at 960 rpm for the first 10 s and then maintained at 160 rpm. All measurements were done in triplicate, and the Thermocline for Windows software was used to obtain pasting viscosity parameters (peak viscosity, breakdown, final viscosity, setback, peak time, pasting temperature). The prepared pastes of starch alone and starch/CFG mixtures were held 1 h at room temperature for the following measurements.

2.4. Swelling power and leached amylose

Swelling power of starch alone and starch/CFG mixture paste was determined in duplicate by modifying the method of Mandala and Bayas (2004). The prepared pastes of 5% starch with deionized water or 0.1, 0.25, 0.5, 1.0% gum mixtures were centrifuged at 16,000 *g* for 20 min. Precipitated pastes were weighed to constant weight in a hot air oven at 105 °C. The swelling power is the ratio of the wet weight of precipitated starch gel to its dry weight. The content of leached amylose in the supernatant was quantified using iodine colorimetric reaction according to Funami et al. (2005a). Supernatant was dissolved in 0.33 M NaOH aqueous solution (6 ml) with heating at 95 °C for 30 min. The solution was mixed with 0.5% trichloroacetic acid to adjust pH to 5.5, and subsequently 0.01 N I_2–KI aqueous solution (0.05 ml) was added. The resultant was read at 620 nm after incubation at room temperature for 30 min using distilled de-ionized water as a reference.

2.5. Rheological measurements

The prepared pastes of starch alone and starch/CFG mixtures (5%) were equilibrated 30 min at room temperature. The resultant paste was loaded onto the plate of an AR1500ex rheometer (TA Instruments, New Castle, DE, USA) and held for 2 min at 25 °C. Steady and dynamic shear modes were conducted at 25 °C using a cone plate geometry system (40 mm diameter, 0.5° cone angle, and 1.000 mm gap). The steady shear tests were performed at the shear rate of 0.1–10 s^{-1}. The frequency sweep tests were performed over an angular frequency of 0.1–10 rad/s at 1% strain (which was in the linear viscoelastic region as determined from stain sweep tests). Before each experiment, a thin layer of silicone oil was applied on the edge of the sample in order to prevent moisture evaporation.

2.6. Differential scanning calorimetry

The gelatinization properties of starch alone and starch/CFG mixtures were measured thermally using DSC (Shimadzu, TA-60 WS, Tokyo, Japan). We prepared powdered starch samples (2.5 ± 0.1 mg) with 7.5 μL of CFG solutions in hermetically sealed aluminum pans, and allowed the solutions to come to equilibrium for 24 h at 4 °C. In the DSC measurements, the prepared pans were heated from 20 to 130 °C at a heating rate of 10 °C/min under a continuous flow of dry N_2 gas, with an empty aluminum pan as a reference. The onset, peak and conclusion temperatures (T_o, T_p and T_c) of gelatinization and gelatinization enthalpy (ΔH_{gel}), were analyzed using Shimadzu TA-60 analysis software.

Table 1
RVA characteristics for maize starch in the presence or absence of each CFG sample.

	Peak viscosity (cP)	Breakdown (mPas)	Final visc (mPas)	Setback (mPas)	Peak time(s)	Pasting temp (°C)
Water & 12.3% starch	4145 ± 0.9[a]	1684 ± 3.4[a]	4259 ± 6.4[a]	1798 ± 4.3[a]	8.2 ± 0.1[a]	72.8 ± 0.1[a]
0.1% CFG & 12.3% starch	3816 ± 9.8[b]	1403 ± 9.8[b]	4192 ± 10.7[a,b]	1762 ± 0.8[a]	8.4 ± 1.2[a]	72.8 ± 0.5[a]
0.25% CFG & 12.3% starch	3730 ± 7.0[c]	1386 ± 5.2[c]	4302 ± 8.3[a,b]	1788 ± 1.7[a]	8.7 ± 0.5[a]	73.0 ± 0.3[a]
0.5% CFG & 12.3% starch	3602 ± 1.3[c,d]	1062 ± 13.1[d]	4509 ± 11.2[b]	1757 ± 9.5[b]	9.33 ± 0.3[a]	73.3 ± 0.2[a]
1.0% CFG & 12.3% starch	3652 ± 8.2[d]	912 ± 4.2[e]	4840 ± 13.5[c]	1800 ± 7.2[a]	9.47 ± 1.0[a]	73.3 ± 0.1[a]

Values are means ± SD of duplicate; values in the same column with different superscripts are significantly different ($p < 0.05$).

2.7. Confocal laser scanning microscopy (CLSM)

Gel images were recorded using a confocal laser scanning microscope (Nikon Instruments Spa, Nikon Eclipse TE 2000-E, Sesto Fiorentino, Italy) described by Zhou et al. (2014) with small modifications. Stock solution of fluorescein 5-isothiocyanate (FITC, Sigma Chemical Co., St. Louis, MO, USA) was prepared by dissolving the 0.2 g FITC in 100 mL distilled water. Starch suspensions (100 μL) with or without CFG addition were respectively stained by mixing with 20 μL FITC stock solution. An aliquot of the stained sample was deposited onto a glass slide and observed within 15 min. A He/Ne and Ar laser with an excitation wavelength of 488 nm for FITC was used. Emission was within 500–525 nm. The objective used for all experiments provided a 20× magnification.

2.8. Data analysis

Each test was performed at least twice, and the reported results were obtained using the SAS system (Version 9.1 for Windows, SAS Institute Inc., Cary, NC, USA). To determine the differences among samples at different measurement points, a t-test for independent samples at a probability level of 0.05 was used ($p < 0.05$).

3. Results and discussion

3.1. RVA characteristics

The RVA characteristics of maize starch in the presence and absence of CFG were listed in Table 1. From Table 1, addition of CFG with different concentration decreased the value of peak viscosity of maize starch comparing to the control. An increasing of CFG concentration contributed to a lower value of peak viscosity, and this value reached a minimum when 0.5% CFG was adding. In addition, comparing to 0.5% CFG, higher viscosity of 1.0% CFG (Carvajal-Millan et al., 2005) could be the reason why the peak viscosity of starch gel with 1.0% CFG slightly increased (from 3602 cP to 3652 cP). It was reported that the peak viscosity would be influenced by the amount of amylose leaching, amylose–lipid complex formation, friction between swollen granules, granule swelling, and competition for free water between leached amylose and remaining ungelatinized granules (Ahmadi-Abhari, Woortman, Hamerc, Oudhuis, & Loos, 2013). A hot composite paste was composed of a continuous phase of dissolved and partially dissolved starch polymer molecules (primarily amylose and low molecular weight amylopectin molecules) and hydrocolloid molecules, and a discontinuous phase of swollen granules and granule fragments (Alloncle and Doublier, 1991; Hermansson & Svegmark, 1996). More amylose would be retained in the discontinuous phase instead of gathering in the continuous phase as the addition concentration of CFG was increasing, and the swelling power of starch granules should be restricted in the presence of CFG. On the other hand, according to Yadav et al., 2007b, the molar mass of CFG was relatively lower (2.9×10^5) when comparing to other hydrocolloids. Most hydrocolloids increased the peak viscosity of starch gels, whereas low molecular mass of guar gum (4.7×10^5) described by Funami et al. (2005b) decreased the peak viscosity because the lower molecular mass of guar realized a smooth flow and prevented the abrasion of starch granules without interacting with amylose or amylopectin leached. Therefore, as CFG presented in the maize starch suspension, decrease in the peak viscosity could be explained by two hypotheses that CFG interacted with amylose and restricted starch granules swelling which directly influenced the peak viscosity, or CFG realized a relatively smooth flow in the continuous phase without interacting with starch molecules.

After starch suspension reached a maximum of viscosity, starch granules began to rupture and break down which resulted in a viscosity decrease. In this study, the higher the concentration of CFG, the lower values of breakdown and the larger values of final viscosity were observed. This result appeared to suggest that the starch granules should become more resistant to thermal treatment and mechanical shearing (BeMiller, 2011). For rice starch-hydrocolloid combinations, including xanthan, guar, sodium alginate, breakdown increased above the control values. A significant decrease in breakdown viscosity of starch might be due to less swelling of the starch granules in the presence of gum (Kaur, Singh, Singh, & McCarthy, 2008). Also, CFG might retard the amylose molecules in the amorphous regions, and the amylose molecules would act as a diluent or inhibitor to alleviate the breakdown of swollen starch granules (BeMiller, 2011). The result of breakdown should support the second hypothesis that CFG restricted starch granules swelling and decreased the peak viscosity values.

The setback and pasting temperature values of starch/CFG remained nearly unchanged when the concentration of CFG was increased from 0 to 1.0%. This result indicated that the addition of CFG insignificantly affected the retrogradation of starch at the cooling stage (Alloncle, LeFebvre, Llamas, & Doublier, 1989). Many studies showed that amylose association was not the only factor responsible for setback, the structure of amylose and amylopectin was reported to play an important role in the pasting properties of starches (Singh, Singh, Isono, & Noda, 2010). The aforementioned interaction between amylose leaching and CFG could not affect the value of setback in this study.

3.2. Leached amylose and swelling power

It can be seen from Table 2 that comparing with the control, the swelling power of starch with 0.1% CFG reduced significantly from

Table 2
The amount of leached amylose and swelling power of gelatinized starch granules in the presence or absence of each CFG sample.

	Leach amylose (%)	Swelling power (g/g)
5% Starch	41.2 ± 1.7[a]	16.49 ± 0.03[a]
5% CS & 0.1%CFG	34.8 ± 1.3[b]	14.76 ± 0.12[b]
5% CS & 0.25% CFG	33.9 ± 0.8[b]	14.54 ± 0.02[b,c]
5% CS & 0.5% CFG	33.4 ± 0.6[b,c]	13.36 ± 0.21[c]
5% CS & 1.0% CFG	31.4 ± 1.0[c]	13.29 ± 0.09[c]

Data are means ± SD of duplicate; values in the same column with different superscripts are significantly different ($p < 0.05$).

Table 3
DSC measurements for gelatinization properties of maize starch-CFG mixtures and starch only.

	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_{gel} (mJ/g)
25% Corn starch (CS)	67.12 ± 0.01[a]	71.79 ± 0.08[b]	76.72 ± 0.22[c]	−11.86 ± 0.56[d]
25% CS/0.1% CFG	67.08 ± 0.13[a]	71.80 ± 0.15[b]	76.62 ± 0.20[c]	−11.50 ± 0.28[d]
25% CS/0.25% CFG	67.16 ± 0.11[a]	71.88 ± 0.06[b]	76.92 ± 0.29[c]	−11.48 ± 0.02[d]
25% CS/0.5% CFG	67.24 ± 0.11[a]	71.81 ± 0.14[b]	76.81 ± 0.21[c]	−11.28 ± 0.19[d]
25% CS/1.0% CFG	67.15 ± 0.10[a]	71.81 ± 0.11[b]	76.79 ± 0.22[c]	−11.77 ± 1.14[d]

T_o, onset temperature; T_p, peak temperature; T_c, conclusion temperature; ΔH_{gel} enthalpy of gelatinization.
Mean values ± standard deviation of triplicates; values followed by the same letters in the same column do not differ significantly at $p < 0.05$ level.

16.49 to 14.76 g/g when starch suspensions were heated to 95 °C. The swelling power decreased to 13.29 g/g when the concentration of CFG was 1.0%. This was in contrast with the finding that maize starch granule swelling was not restricted in the presence of low concentrations of gum (such as 1%) because there were enough water molecules for starch-gum mixture swelling (Kaur et al., 2008).

The amount of leached amylose for each starch/CFG system was significantly lower than that for the control (41.2 ± 1.7%) (Table 2). This result was similar to the changes previously reported in the wheat starch/polysaccharides system, and Funami et al. (2005a) suggested that these polysaccharides increased the viscosity of the continuous phase and prevent the diffusion of amylose from starch granules. In this study, amylose in a helical conformation had the ability to form inclusion complexes with components like fatty acids and phospholipids (Eliasson, 1998; Ahmadi-Abhari et al., 2013). CFG samples contained sterol-fatty acid esters, triacylglycerols and free fatty acids (palmitic and oleic acids), and the total amount of lipids varied from 2555 to 4289 μg per gram CFG (Yadav et al., 2007b). The fatty acids were esterified to the arabinoxylan and proteins in CFG (Yadav et al., 2007a). In starch gel granules, the swollen amylopectin-enriched granules were embedded in a matrix of entangled amylose molecules (Nagano et al., 2008; Zhou et al., 2014). Combining with the poorer swelling power of gelatinized starch-CFG composite, our results showed that CFG was absorbed by the granules before reaching the gelatinization temperature and possibly formed rather stable inclusion complexes with amylose, and this formation might testify the RVA results in Section 3.1.

3.3. Thermal properties

T_o, T_p, and T_c and ΔH_{gel}, calculated from the DSC thermograms are listed in Table 3. Statistical analysis from DSC data showed that there was no significant difference among various starch blends and control sample. This was in agreement with the evidence that the arabinoxylan from rye flour, at addition levels of 1–2%, had a negligible effect on the thermal properties of maize, potato and wheat starch (Gudmundsson et al., 1991). It was also found that, in most cases, hydrocolloids had little or no effect on gelatinization temperatures and enthalpy (BeMiller, 2011). According to Yoshimura et al. (1996), T_o and T_c were independent of starch concentration, whereas T_c shifted to lower temperatures with decreasing concentration over the range of maize starch concentration 1–50%, and ΔH_{gel} was almost independent of starch concentration less than 40%. In the other case, the arabinoxylan extracted and purified from wheat (1–2% w/w on a starch basis) increased the phase-transition temperature range and ΔH_{gel} of 40% w/w wheat starch (Biliaderis et al., 1997). According to Gudmundsson et al. (1991), the effects

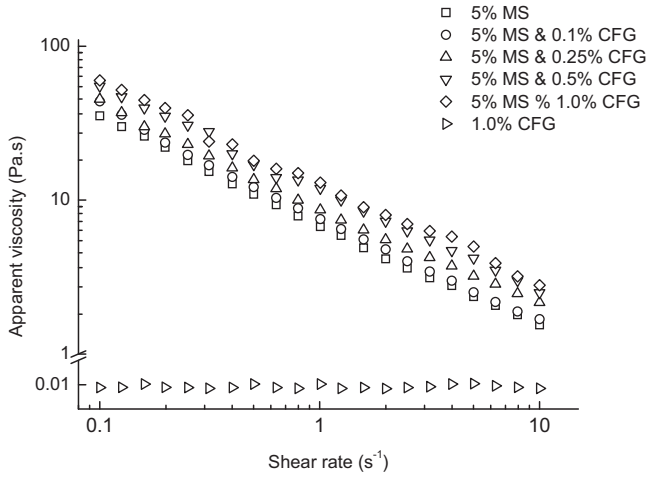

Fig. 1. Effect of CFG concentration on the apparent viscosity of maize starch–CFG mixtures at 25 °C (MS stands for maize starch).

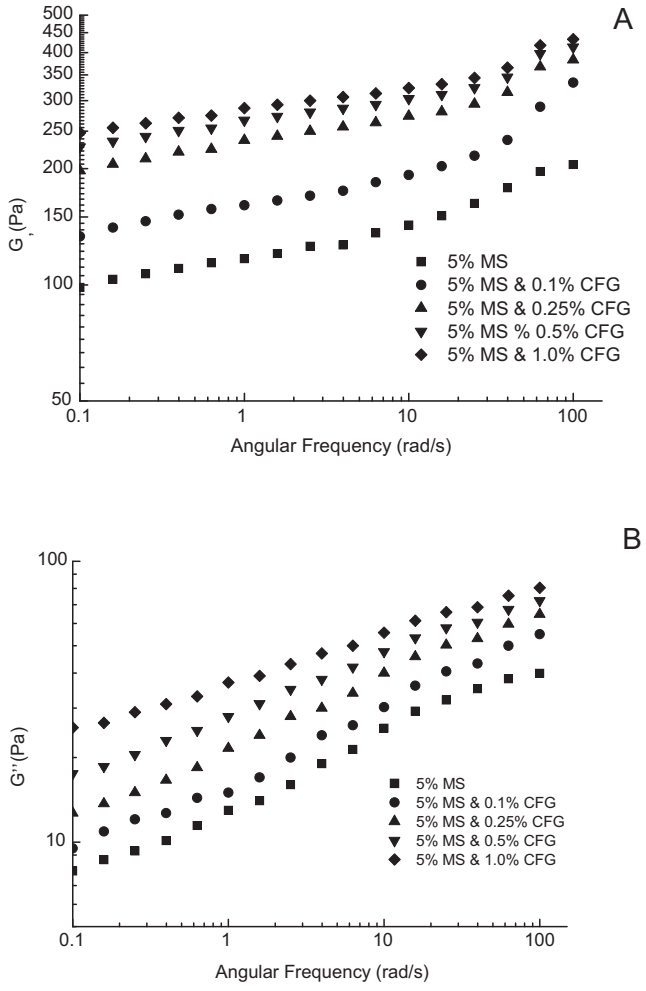

Fig. 2. Variation of G' (A), G'' (B) with angular frequency at 25 °C for 5% maize starch (MS) gel and maize starch–CFG mixtures.

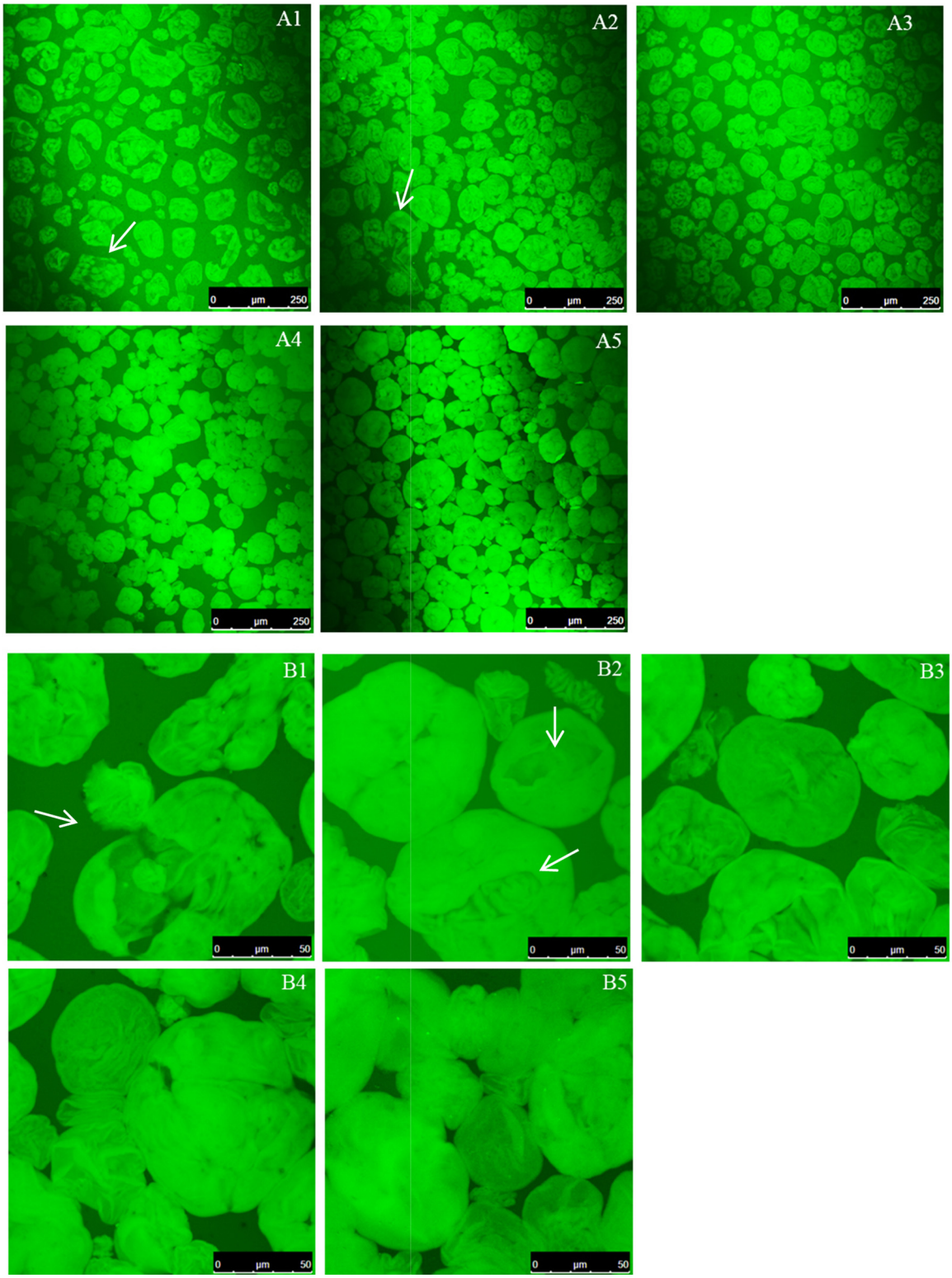

Fig. 3. CLSM images of maize starch (5% w/w) containing 0 (A1, B1), 0.1% (A2, B2), 0.25% (A3, B3), 0.5% (A4, B4) and 1.0% (A5, B5) CFG (w/v).

of arabinoxylan addition were dependent on the initial starch concentration, and water soluble arabinoxylan absorbed 9–11 times their own weight of water. In general, the competition for water between starch and hydrocolloid could decrease the gelatinization enthalpy when the water content is lower than 50%. In this study, samples were prepared at 70% moisture content, ΔH_{gel} of starch alone and starch/CFG mixtures are ranged from 11.28–11.86 mJ/g and corresponds well with the ΔH_{gel} of 11.4 mJ/g reported by Shiotsubo & Takahashi (1984) and 11.5 mJ/g reported by Yoshimura et al. (1996) (maize starch (33% w/w), amylose content, 24% and 25% respectively). This moisture dependent gelatinization process and low concentration of CFG could be the reason why the thermal characteristics of starch/CFG mixtures are effectively constant. What is more, CFG contained 4%–9% protein, and protein

components were highly consistent with commercial corn zein (Yadav et al., 2007b). Only under limited water content (35% w/w), zein would acted as competitors for water uptake and changed the DSC characteristics of starch gelatinization (Kim & Wang, 1999).

3.4. Rheological properties

From Fig. 1, it can be seen that the 5% (w/w) maize starch paste with or without CFG addition displays shear thinning behaviors, suggesting that all samples exhibit non-Newtonian behavior. The low viscosity of CFG changed insignificantly as the shear rate increasing when compared with starch. Furthermore, the apparent viscosity of CFG-maize starch mixtures was increased with increasing of CFG concentration (from 0.1 to 1.0%). This result might be attributed to the intermolecular interaction between arabinoxylan and maize starch molecules during pasting (Wang et al., 2008), a continuous network contributed by CFG might be retained within the peripheral layers of the swollen granules to yield a higher viscosity. Phase separation favored interactions between like molecules, but this effect might be masked by starch–hydrocolloid intermolecular interactions (BeMiller, 2011). Due to the increased viscosity of the continuous phase, phase separation between amylopectin and CFG molecules (according to Yakeda et al. (1987), M_w of corn amylopectin was $40–80 \times 10^6$ Da, of corn amylose, 1.2×10^5 Da) could happen as well.

Higher CFG adding concentration brought about larger values of G' with frequency for the CFG-maize starch mixture comparing to the starch only gel (Fig. 2A). Addition of 1.0% CFG boosted the G' values of starch paste up to 2.5-fold at an angular frequency of 10^{-1} rad/s. It was reported that, before the re-crystallization of starch gel occured, the size of the crystalline lamellae in amylopectin cluster was observed to increase with increasing amylose content (Lu, Donner, Yada, & Liu, 2012) and the rigidity of starch granule structure was in proportion to its amylose content but in inverse proportion to the degree of granule swelling (BeMiller, 2011). The results of swelling power and leached amylose of starch/CFG mixtures in Section 3.2 should explain why the G' increased with the increasing CFG concentration in this study.

As the angular frequency of oscillatory was increasing, the increase in G' was accompanied by a corresponding increase in G'', and the rising G' and G'' curves were almost parallel (Fig. 2B). The storage modulus G' was a measure of the energy that was stored in the material or recoverable per cycle of deformation, G'' was a measure of the energy that was lost as viscous dissipation per cycle of deformation. For all samples, the magnitudes of elastic portion (characterized by G') were an order of magnitude larger than those of viscous flow (characterized by G'') over the range of dynamic frequency studied, and a crossover between the two moduli was not discovered. These observations also suggested that the increasing concentrations of CFG from 0.1 to 1.0% ensure the CFG-maize starch mixture gel for a predominantly elastic behavior, and both the maize starch and CFG-maize starch mixtures had a typical biopolymer gel network as the separation of two module ($\tan\delta = G''/G'$) was smaller than 0.1 (Wang et al., 2008). In the presence of CFG, frequency-dependence of both moduli was greater, indicating a depression of gel-like structure or a weak gel character, which was reported in previous publications on the rheology of hydrocolloids–starch gels (BeMiller, 2011). Intermolecular interactions between like molecules resulted in a macroscopic phase separation. Thermodynamic incompatibility of CFG and starch components might result in a phase separation (Funami et al., 2005a), the effective concentration of polymers in their respective micro phases was raised to cause viscosity properties (G'') enhancement.

3.5. Confocal laser scanning microscopy

CLSM images of 5% maize starch gels in the absence and presence of CFG were depicted in Fig. 3. For the native starch (A1, B1), a fibrillar network of starch gel was formed in the spongy structure. Starch gels had unevenly pores which were very clearly defined, and the existence of starch remnants obscured the border of starch granules. Also, swollen starch granules in gel were observed to be larger than those in gel that contained CFG. By contrast, when maize starch granules were gelatinized in CFG solution, starch components tended to be inhibited from leaching out of the granules, the granule remnants were observed to form close network. The starch gels containing 0.1% and 0.25% CFG appeared to have smaller and less well-defined pores embedded in a strong matrix (B2, B3). The granule in starch/1.0% CFG composite seemed to be much more compact than control (B5). These structural findings were correlated well with what was observed in the measurements of leached amylose and swelling power. Also, the CLSM results were in good agreements with previous findings that the SEM figures of freeze-dried starch-cassia gum pastes presented a shrunken and tight arrangement of the starch granule remnants (Kaur et al., 2008). As starch molecules were associated by hydrogen bonding, water penetrated inside starch granules while heating, driven by differences in osmotic pressure, leading to disruption of the chain hydrogen bonds and release of internal starch polymers (Charoenrein, Tatirat, Rengsutthi, & Thongngan, 2011; Nagano et al., 2008). It was suggested that hydrocolloids, such as xanthan gum, was capable of enwrapping the starch granules and physically stabilizing the particle by acting as a protecting or lubricating 'barrier' (Chaisawang & Suphantharika, 2005; Heyman, Depypere, Meeren, & Dewettinck, 2013). The viscous phase surrounding the swollen starch granules might be hydrocolloids interacting with leached amylose (Charoenrein et al., 2011; Funami et al., 2005a, 2008), the interaction could be attributed to amylose–lipid complex or chain entanglements in this study. The 'thickness' and 'uniformity' of starch granules could adversely relate to the moisture uptake.

4. Conclusions

It is concluded that the properties of maize starch/CFG system and CFG concentration were highly correlated to some rheological and structural properties of starch/CFG gel. The decreasing amount of leached amylose indicated that more amylose would be retained in the starch granule instead of gathering in the continuous phase as the addition concentration of CFG was increasing. This phenomenon would contribute to lower peak viscosity, smaller swelling power and a predominantly elastic behavior. Chain entanglements between CFG and either amylose or short-chain amylopectin and amylose–lipid complex formation possibly happened in the CFG-maize starch composite system. These results of current study suggested the potential for enlarging the use of CFG to modify the properties of starch-based food (e.g. doughs used for baking or starch–hydrocolloid composite films) in food industry. Moreover, the effects of CFG on the retrogradation behavior of starch will be studied in our future study.

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