1 **Comparison of emulsifying properties of food-grade**
2 **polysaccharides in oil-in-water emulsions: Gum arabic, beet**
3 **pectin, and corn fiber gum**

4
5 **Long Bai^{a,b}, Siqi Huan^a, Zhiguo Li^{*,a}, David Julian McClements^{*,b}**

6
7 ^a *College of Material Science and Engineering, Northeast Forestry University, Harbin*
8 *150040, PR China*

9 ^b *Biopolymers and Colloids Laboratory, Department of Food Science, University of*
10 *Massachusetts, Amherst, MA 01003, USA*

11
12
13 **Journal:** Food Hydrocolloids

14 **Submitted:** September 2016

15
16
17
18 **Corresponding author:** David Julian McClements, **E-mail address:**

19 mcclements@foodsci.umass.edu; **Telephone:** 413 545 1019

20 **Corresponding author:** Zhiguo Li, **E-mail address:**

21 lizgmse@nefu.edu.cn

Abstract

Emulsions are utilized in the food, pharmaceutical, and personal care industries to provide specific physicochemical properties and functional attributes. In many applications, it is desirable to use natural ingredients to formulate emulsions to create “label-friendly” products. In this study, the impact of three polysaccharide-based emulsifiers on the formation and stability of oil-in-water emulsions prepared using high-pressure microfluidization were compared: gum arabic, corn fiber gum, and beet pectin. The surface activities of these emulsifiers were characterized using interfacial tension measurements. The influence of emulsifier type, concentration, and homogenization pressure on the efficiency of emulsion formation was examined. The impact of oil type (medium chain triglycerides, corn oil, fish oil, and lemon oil) on the ability of the different emulsifiers to form emulsions was also investigated. The stability of the emulsions was monitored during storage at ambient temperature. Emulsions could be produced using all three polysaccharide-based emulsifiers, with the mean particle diameter decreasing with increasing emulsifier concentration and homogenization pressure. Gum arabic and beet pectin were more effective emulsifiers than corn fiber gum, with a lower amount of emulsifier required and smaller droplets being produced. This effect was attributed to a greater reduction in interfacial tension and stronger adsorption leading to more efficient droplet disruption and less re-coalescence within the homogenizer for gum arabic and beet pectin. Emulsions prepared using corn fiber gum were susceptible to flocculation and coalescence. This study provides valuable information for choosing polysaccharide-based emulsifiers for utilization in food and beverage industries.

Keywords: Polysaccharides, corn fiber gum, beet pectin, emulsions, stability

1. Introduction

Oil-in-water emulsions are integral parts of many products in the food and beverage industries, including milks, creams, dressings, desserts, sauces, dips, and beverages (Dickinson, 2015; McClements, 2015). They are thermodynamically unstable colloidal systems consisting of small oil droplets dispersed within an aqueous phase (McClements, 2015). Emulsifiers are therefore required to provide kinetic stability by coating the oil droplets and generating repulsive interactions (steric or electrostatic) that inhibit droplet aggregation (Jafari, Assadpoor, He, & Bhandari, 2008). Furthermore, emulsifiers facilitate emulsion formation by adsorbing to droplet surfaces and reducing the interfacial tension, thereby facilitating droplet breakup (Kralova & Sjöblom, 2009). Numerous food-grade emulsifiers are legally approved for commercial utilization within the food industry (Hasenhuettl & Hartel, 2008; Kralova, et al., 2009). However, they vary in their costs, ease of use, and functionality, which makes it challenging for food manufacturers to select the most appropriate emulsifier for a particular application. Therefore, it is important to characterize the performance of different emulsifiers under standardized conditions so as to provide the information manufacturers need to make informed choices when selecting emulsifiers (McClements, 2007).

Consumers are increasingly demanding label-friendly products fabricated from natural and sustainable ingredients, which has stimulated interest in replacing synthetic surfactants with natural emulsifiers in many food and beverage applications (De, Malik, Ghosh, Saha, & Saha, 2015; McClements & Gumus, 2016; Ozturk & McClements, 2016). Biopolymer-based emulsifiers, such as amphiphilic proteins and polysaccharides, are particularly promising natural candidates to form and stabilize emulsions in food and other applications. Protein-based emulsifiers are already commonly used in industrial applications due to their wide range of sources and good emulsifying ability (Dickinson, 2015; Lam & Nickerson, 2013). Nevertheless, there are important limitations to using

protein-based emulsifiers in many food products, for example, protein-coated oil droplets are usually unstable at pH values around their isoelectric point, at high ionic strengths, and at elevated temperatures (McClements, 2004; McClements, et al., 2016). Certain types of polysaccharide-based emulsifiers are also commonly used in the food industry as natural emulsifiers, such as gum arabic, corn fiber gum, and beet pectin (Ngouemazong, Christiaens, Shpigelman, Van Loey, & Hendrickx, 2015; Williams & Phillips, 2009; Yadav, Johnston, & Hicks, 2009).

Gum arabic is one of the most widely used amphiphilic polysaccharides in the food industry (Reiner, Reineccius, & Peppard, 2010; Williams, et al., 2009). Unlike protein-based emulsifiers, gum arabic is not highly sensitive to aggregation at intermediate pH values, high ionic strengths, and high temperatures due to the formation of thick steric stabilizing layers around the oil droplets (Ozturk, Argin, Ozilgen, & McClements, 2015; Williams, et al., 2009). However, one significant issue is that it is difficult to use low levels of polysaccharides to produce emulsions with small droplet sizes (Charoen, et al., 2011). Furthermore, at high emulsifier concentrations, depletion flocculation caused by non-adsorbed polysaccharide molecules may negatively affect the shelf life of finished products (Chanamai & McClements, 2001). The utilization of gum arabic isolated from the *Acacia Senegal* tree has also been limited due to fluctuations in the availability, quality, and cost of the raw material (Williams, et al., 2009). Therefore, identifying and developing new types of polysaccharide-based emulsifiers that can be used to produce edible emulsions is important. In this study, we investigated the emulsifying ability of two natural polysaccharide-based emulsifiers, corn fiber gum and beet pectin, to explore the possibility to replace gum arabic in the preparation of oil-in-water emulsions.

Corn fiber gum (CFG) is a low value by-product of the corn milling process (Yadav, Johnston, Hotchkiss, & Hicks, 2007b; Yadav, Parris, Johnston, Onwulata, & Hicks, 2010). Chemically, CFG is an arabinoxylan (also called hemicellulose B) consisting of a main chain of β -1,4 linked D-xylopyranose units with α -L-arabinofuranosyl units linked at the 2

or 3 positions (Kokubun, Yadav, Moreau, & Williams, 2014). It also contains lesser amounts of galactose, glucose, glucuronic acid and rhamnose residues. It has been shown that corn fiber gum also contains a small proportion of hydrophobic phenolic acid residues, lipids, and proteins as part of its molecular structure, which may lead to surface activity and emulsifying properties (Yadav, Johnston, & Hicks, 2007a; Yadav, Parris, Johnston, & Hicks, 2008). Furthermore, certain types of corn fiber gum have been reported to have a relatively low solution viscosity and high solubility (Yadav, Strahan, Mukhopadhyay, Hotchkiss, & Hicks, 2012; Zhang, et al., 2015a). The emulsifying ability of corn fiber gum has been reported in a number of previous publications (Cirre, Al-Assaf, Phillips, Yadav, & Hicks, 2014; Yadav, et al., 2009; Yadav, et al., 2007b).

Pectin is a natural heterogeneous anionic plant polysaccharide mainly located in the primary cell wall and middle lamella of higher plants, which has been widely used in the food industry because of its gelling, thickening, and stabilizing properties.

(Ngouemazong, et al., 2015). Pectin has a complex structure that depends on both its biological source and the extraction process (Leroux, Langendorff, Schick, Vaishnav, & Mazoyer, 2003). Compared to other types of pectin commonly used in the food industry, sugar beet pectin has a higher content of acetyl groups at O-2 and O-3 positions within the galacturonic backbone, a higher content of phenolic esters in the lateral chains, and a higher amount of covalently bound proteins in the lateral chains (Leroux, et al., 2003; Nakauma, et al., 2008). The presence of the phenolic and protein groups on sugar beet pectin mean that it can adsorb to oil-water interfaces and reduce the interfacial tension (Gülseren & Corredig, 2014; Zhang, et al., 2015b). Indeed, it has been reported that the adsorption of beet pectin to oil droplet surfaces increases with protein content (Siew, Williams, Cui, & Wang, 2008). The beet pectin-layer formed around the oil droplets provides electrostatic and steric repulsion, which helps to prevent droplets from flocculation and coalescence (Chen, et al., 2016). One significant advantage of beet pectin is that it can be used at lower levels than gum arabic to stabilize emulsions

(Burapapadh, Kumpugdee-Vollrath, Chantasart, & Sriamornsak, 2010; Funami, et al., 2011).

In this study, we characterized the emulsifying properties of the three polysaccharide-based emulsifiers in oil-in-water emulsions prepared by microfluidization. The influence of polysaccharide type and concentration, oil type, and homogenization conditions on the formation of oil-in-water emulsions was studied. Also the influence of the polysaccharides on the stability of the emulsions to droplet growth and gravitational separation was determined. The results obtained provide valuable information for choosing appropriate polysaccharide-based emulsifiers for application in the food and beverage industries.

2. Experimental

2.1. Materials

Gum arabic was provided by TIC Gums (Belcamp, MD). The manufacturer reported that this ingredient contained around 6.7% moisture, 90% polysaccharide, 3.2% protein, and 0.2% minerals. Beet pectin was kindly provided by Herbstreith & Fox KG (Germany). The manufacturer reported that this ingredient had a galacturonic acid content of 66.4%, a degree of esterification of 54.3%, a methylester content of 5.8%, a protein content of 2.9%. Corn fiber gum was provided by Z Trim Holding Inc. (Mundelein, IL). The manufacturer reported that corn fiber gum ingredients typically contain around 7.9% moisture, 6.3% protein, 9.0% starch, 3% fat, and 81% fiber (Yadav, et al., 2014). Corn oil (Mazola) was purchased from a local grocery store. The molecular weights of the same gum arabic, beet pectin and corn fiber gum ingredients used in the current study were measured by size exclusion chromatography in another study to be 502, 417, and 291 kg mol⁻¹, respectively (Bai, Liu, Xu, Huan, & McClements, 2017). The radius of hydration of the ingredients measured in the same study were 12.3, 23.8 and

19.9 nm, respectively. Fish oil was kindly provided by DSM Inc. (Columbia MD). Lemon oil (3-fold and 10-fold) was kindly provided by International Flavors and Fragrances (Union Beach, NJ). Medium chain triglycerides (MCT, Miglyol 812N) were purchased from the Warner Graham Co. (Cockeysville, MD). Sodium phosphate monobasic and Nile red were purchased from Sigma-Aldrich Co. (St. Louis, MO). Double distilled water (Milli-Q) was used to prepare all solutions and nanoemulsions.

2.2. Emulsion preparation

An aqueous phase was prepared by dissolving polysaccharide (0.1-5.0 wt%) in buffer solution (10 mM sodium phosphate, pH 7.0), which resulted in pH values around 5.5 to 7 depending on polysaccharide type and concentration. Oil-in-water emulsions were then prepared by homogenizing 10 wt% oil phase (corn oil, MCT, fish oil, or lemon oil) with 90 wt% aqueous phase. A coarse emulsion was prepared by blending oil and aqueous phases together using a high shear mixer (Bamix, Biospec Products, Bartlesville, OK) for 2 min at ambient temperature. Fine emulsions were then formed by passing coarse emulsions through an air-driven microfluidizer equipped with a Y- and Z-type interaction chamber (Microfluidics PureNano, Newton, MA, USA). The coarse emulsions were fed into the microfluidizer using a 100 ml glass reservoir (pressurized by an intensifier pump, flow rate 500 ml per minute), and then passed through the homogenization chamber three times at certain homogenization pressures (9-19 kpsi).

2.3. Determination of particle size

The particle size distribution of the emulsions was measured using static light scattering (Mastersizer 2000, Malvern Instruments, Malvern, UK). Emulsions were diluted with buffer solutions of the appropriate pH prior to analysis to avoid multiple scattering effects. The refractive indices (RI) of aqueous phase and different oil phases used in the calculations were listed in Table 1 (Bai & McClements, 2016b). The droplet

diameter of each sample was represented as the volume-weighted mean diameter (d_{43}) or surface-weighted mean diameter (d_{32}), which was calculated from the full particle size distribution.

2.4. Rheological measurements

The rheology of prepared emulsions was characterized using a dynamic shear rheometer with a cup-and-bob measurement cell (Kinexus, Malvern, Worcestershire, UK). The tested temperature throughout this experiment was 25 °C. A constant shearing rate (10 s^{-1}) and test time (3 min) were used for all measurements.

2.5. Interfacial tension measurements

The interfacial tension of different polysaccharide solutions was measured at corn oil-water interfaces using a drop shape analysis instrument (DSA 100, Kruss GmbH, Hamburg Germany). According to our previous measuring method (Bai, Huan, Gu, & McClements, 2016a), we then used an incubation time of 15 min or complete detachment of oil drop from the needle for all of the subsequent experiments. The polysaccharide concentration range used was from 0.0005% to 0.1% since over 0.1% the corn fiber gum and beet pectin solutions were not sufficiently transparent to make reliable measurements. The surface pressure (π) was calculated from the interfacial tension (γ) data using the following equation: $\pi = \gamma_0 - \gamma$, where γ and γ_0 are the interfacial tensions measured in the presence and absence of polysaccharides. The γ_0 value measured at the corn oil - aqueous phase interface was 28 mN/m.

2.6. Microscopy measurements

The microstructure of emulsion samples was examined using confocal scanning fluorescent laser microscopy with a 60× objective lens and optical microscope with a 40× objective lens (Nikon D-Eclipse C1 80i, Nikon, Melville, NY, U.S.). Emulsion samples

were stained with a fluorescent dye prior to observation. The oil phase was dyed by adding 10 μ L of Nile red solution (1 mg/mL ethanol) to 500 μ L of emulsion samples. After homogeneously mixing by pipette, 6 μ L of dyed emulsion was placed on a microscope slide and covered with a glass cover slip. The cover slip was quickly fixed by nail polish to avoid evaporation. The excitation and emission **wavelength** for Nile red were 543 nm and 605 nm, respectively. The microstructure images were acquired and then analyzed using image analysis software (NIS-Elements, Nikon, Melville, NY).

2.7. Emulsion stability

Emulsion samples were placed in glass test tubes and then incubated at ambient temperature (25 °C) prior to observation. The emulsion stability was monitored at day-0 (soon after preparation), day-1 (stored for 24h), and day-7 (stored for 7 days), respectively. The particle size distribution of the samples was then measured by light scattering as described earlier, and the creaming stability was determined by visual observation. **For the light scattering experiments, the emulsions were vortexed for 5 seconds before removing a sample to ensure they were homogeneous.**

2.8. Statistical analysis

All measurements were performed on at least two freshly prepared samples with three measurements per sample and are reported as means and standard deviations.

3. Results and discussion

3.1. Interfacial characteristics of polysaccharides

The interfacial characteristics of surface-active ingredients are a significant factor in determining their ability to form and stabilize emulsions (Dickinson, 2003; Rodríguez Patino, Rodríguez Niño, & Sánchez, 1999). We therefore measured the interfacial tension

of corn fiber gum, beet pectin and gum arabic at different concentrations to obtain a better understanding of their interfacial characteristics at corn oil-water interfaces (Fig. 1). The interfacial tension was determined using drop shape analysis as described previously (Bai, et al., 2016a; Bai, et al., 2016b). For all of the polysaccharides, the interfacial tension decreased with increasing concentration, indicating that they adsorbed to the corn oil-water interface (Fig. 1). However, the different emulsifiers showed appreciable differences in their ability to lower the interfacial tension. For gum arabic and beet pectin, a fairly similar interfacial tension (around 18 mN/m) was reached at high emulsifier concentrations. On the other hand, the interfacial tension of the corn fiber gum was still relatively high (around 24 mN/m) at the highest emulsifier concentrations, which indicates that it was less effective at decreasing the interfacial tension. It should be noted that polysaccharides are usually less effective at reducing the interfacial tension than proteins or small molecule surfactants because they are less able to screen the thermodynamically unfavorable contacts between non-polar groups and water (McClements, 2015). A number of other studies have also reported that polysaccharides do not usually lead to a large reduction in interfacial tension, which can be attributed to the same reason (Castellani, Al-Assaf, Axelos, Phillips, & Anton, 2010a; Vasile, Martinez, Ruiz-Henestrosa, Judis, & Mazzobre, 2016). It should also be stressed that the interfacial tension of the oil droplets formed within a homogenizer may not be the same as that measured in a static interfacial tension meter due to the finite time taken for the emulsifier molecules to adsorb to the droplet surfaces (Walstra, 1993). Consequently, the impact of emulsifier type on droplet disruption depends on both the ability to reduce the interfacial tension and the adsorption rate inside the homogenizer.

Overall, our measurements show that the gum arabic and beet pectin exhibited fairly similar interfacial characteristics, and both were more effective than corn fiber gum at reducing the interfacial tension of the corn oil-water interface.

3.2. Formation of polysaccharide-stabilized emulsions

3.2.1 Influence of polysaccharide type and concentration on formation of emulsion

The influence of polysaccharide type and concentration on the formation of corn oil-in-water emulsions produced using standardized homogenization conditions was initially investigated (Fig. 2). Emulsions could not be prepared using corn fiber gum or beet pectin at concentrations greater than 5 and 2 wt% respectively, because they were too viscous to pass through the microfluidizer. Therefore, 5 wt% corn fiber gum and 2 wt% beet pectin were the maximum levels used in this study. There was a decrease in mean particle diameter (d_{43}) with increasing emulsifier concentration for all three polysaccharide emulsifiers, with the profile depending on emulsifier type (Fig. 2a). The particle size distributions of emulsions fabricated using standardized homogenization conditions were also measured (Fig. 2b-d). Monomodal particle size distributions were obtained for gum arabic and beet pectin even at 0.1 wt% emulsifier. Conversely, bimodal distributions were observed for corn fiber gum at the lower concentrations used (0.1-0.5 wt%), but monomodal distributions were observed at higher levels.

The observed decrease in mean droplet diameter with increasing emulsifier concentration can be attributed to two main reasons: (i) a greater droplet surface area can be covered during homogenization leading to smaller droplets sizes (Tcholakova, Denkov, & Danner, 2004); (ii) droplet surfaces can be covered more rapidly, thereby reducing droplet re-coalescence within the homogenizer (Jafari, et al., 2008). However, the dependence of droplet diameter on polysaccharide concentration was quite different for emulsions formed using the three emulsifiers (Fig 2a). For gum arabic and beet pectin, the droplet diameter-emulsifier concentration profile followed the expected two-region dependence: *Region I* - the particle size decreases with increasing emulsifier concentration due to increased surface coverage; *Region II* - the droplet diameter remains fairly constant because the homogenizer cannot produce smaller droplets (Tcholakova, et al., 2004). The minimum droplet diameters (d_{43}) at 3% gum arabic and 1% beet pectin were 0.76 and 0.31 μm , respectively. However, for the corn fiber gum, the droplet

diameter-emulsifier concentration profile only appeared to exhibit Region I, suggesting that the droplet diameter was limited by emulsifier type across the whole emulsifier concentration range used. The minimum droplet diameter (d_{43}) obtained at 5% corn fiber gum was relatively large (4.80 μm), indicating that this ingredient was not an effective emulsifier.

Differences in the minimum amount of emulsifier required to reach a constant droplet diameter (C_{min}), and in the minimum droplet diameter produced (d_{min}) can be ascribed to differences in the nature of the emulsifiers. The higher C_{min} and d_{min} values for gum arabic than for beet pectin can be attributed to the larger molecular weight of gum arabic because their interfacial properties were otherwise similar. Furthermore, beet pectin has an extended configuration and a semi-flexible chain with radius of gyration of 44 nm (Funami, et al., 2007) whereas gum arabic has a globular, coil configuration with radius of gyration of 28 nm (Castellani, Al-Assaf, Axelos, Phillips, & Anton, 2010b). So, beet pectin may adsorb faster and cover the oil droplet surfaces better than gum arabic at lower concentrations. However, for corn fiber gum, the much higher C_{min} and d_{min} values is mainly caused by the large molecular weight, lower surface-activity, and higher interfacial tension. **As a result, there may have been less droplet breakup and more droplet re-coalescence during homogenization, leading to larger droplet sizes (Maindarkar, Bongers, & Henson, 2013).**

The surface load of the emulsifier at saturation (Γ) is an important parameter for understanding the formation of emulsions. When the droplet diameter is limited by the emulsifier level, the minimum emulsifier concentration required to cover all the droplets produced is given by (McClements, 2007):

$$\Gamma = \frac{d_{32} \times C_s}{6 \times \varphi} \quad (2)$$

where C_s is the concentration of emulsifier in the emulsion (kg/m^3), Γ is the surface load of the emulsifier at saturation (kg/m^2), φ is the dispersed phase volume fraction (dimensionless), and d_{32} is the surface-weighted mean droplet diameter (m) produced by

the homogenizer. This equation assumes that all of the emulsifier molecules are adsorbed to the droplet surfaces and that adsorption occurs extremely quickly during homogenization, which is unlikely to occur in practice for large molecules like polysaccharides. Consequently, the calculated surface loads should only be considered to be effective values. Nevertheless, these effective surface loads are useful for comparing the relative effectiveness of different types of emulsifiers in commercial applications.

Equation 2 was used to calculate the surface load of the polysaccharides based on the oil droplet concentration ($\varphi = 0.1$), emulsifier concentration (0.1 to 5 wt%, or 1 to 50 kg/m³), and measured mean droplet diameters (d_{32}). The calculated surface loads of gum arabic and beet pectin were 31 and 4.5 mg/m², respectively, indicating that the effective surface load of beet pectin was about ten times smaller than that of gum arabic, which can be attributed to differences in the molecular weight and packing of the emulsifier molecules at the oil-water interface. For corn fiber gum, the effective surface load was 352 mg/m², which was much larger than that of gum arabic and beet pectin. This relatively high value can at least partly be attributed to the fact that a large fraction of the corn fiber gum molecules was not adsorbed to the oil droplet surfaces and still existed in the continuous aqueous phase. This may have occurred because the CFG molecules were not highly surface active and therefore did not attach strongly to the droplet surfaces, and because they were relatively large and therefore only adsorbed slowly.

Another possible reason for the observed differences in the emulsification properties of the different polysaccharide emulsifiers is their impact on the rheology of the aqueous phase. The rheological properties of the aqueous phase may impact the flow profile within the homogenizer, and thereby alter droplet disruption processes (Walstra, 1993). However, it should be highlighted that aqueous polysaccharide solutions are typically highly shear thinning, and therefore the viscosity of a polysaccharide solution within a homogenizer will be very different from that measured in a typical rheometer.

3.2.2 Influence of polysaccharide type and concentration on emulsion rheology

The rheological characteristics of emulsions are important for certain applications (McClements, 2015; Pal, 2011). Therefore, we investigated the influence of the concentrations of gum arabic, corn fiber gum, and beet pectin on the viscosities of the emulsions (Fig. 3). The increase in viscosity with increasing emulsifier concentration followed the following trend: beet pectin > corn fiber gum > gum arabic. These results indicate that there were important molecular and structural differences among the three polysaccharides used. In general, the ability of polysaccharides to increase viscosity depends on their molecular weight, conformation, and interactions. The beet pectin, corn fiber gum, and gum arabic used in this study have recently been reported to have molecular weights of 417, 291, and 502 kg mol⁻¹ and radius of hydration of 23.8, 19.9 and 12.3 nm, respectively (Bai, et al., 2017). Thus, the differences in molecular weight do not account for the observed differences in rheology, but the differences in radius of hydration do seem to be correlated to viscosity. The relatively low viscosity of gum arabic solutions can be attributed to the fact that these molecules are highly branched and therefore have a relatively low radius of hydration and effective volume (Li, et al., 2009; Phillips & Williams, 2009; Sanchez, Renard, Robert, Schmitt, & Lefebvre, 2002). Corn fiber gum is also a highly branched polysaccharide (Zhang, et al., 2015a), which would account for the fact that it has a lower viscosity than beet pectin, even though it has a higher molecular weight, because its more compact structure leads to a lower radius of hydration and effective volume. The high viscosity of the beet pectin emulsions may be attributed to its high radius of hydration (effective volume) or chain associations caused by hydrophobic attraction between ester groups and hydrogen bonding between hydroxyl groups (Williams, et al., 2005).

3.2.3 Influence of polysaccharides on formation of emulsions with different oil types

Different types of oils may be used to produce emulsions in the food and other industries. Therefore, we examined the influence of oil type on the formation of

emulsions stabilized by gum arabic, corn fiber gum, and beet pectin (Fig. 4). All of the polysaccharides could be successfully used to prepare oil-in-water emulsions with different oil types. In particular, gum arabic and beet pectin could be used to form emulsions with small droplet diameters using all types of oil. The mean droplet diameters of emulsions prepared from corn oil, MCT, or fish oil were fairly similar being around 0.8 μm for gum arabic and around 0.3 μm for beet pectin. However, the mean droplet diameters of the emulsions prepared from lemon oil (3 $\times$ or 10 $\times$) using these two emulsifiers were considerably larger, which may have been due to Ostwald ripening effects occurring during and after homogenization (Rao & McClements, 2012; Wooster, Golding, & Sanguansri, 2008; Zhang, Bing, & Reineccius, 2016). This effect occurs because lemon oils have a relatively high water-solubility and therefore the oil molecules can rapidly diffuse between the oil droplets leading to the growth of large droplets at the expense of small droplets due to a thermodynamic effect associated with interfacial curvature (McClements, 2015). The emulsions prepared using corn fiber gum contained much larger droplets than those prepared using beet pectin and gum arabic for all oil types. Nevertheless, a similar relative dependence of mean droplet diameter on oil type was observed for all three polysaccharides (Fig. 4).

3.3. Influence of homogenization pressure on formation of emulsions

Numerous studies have shown that the size of droplets produced by high-pressure microfluidization depend on homogenization conditions (Lee, Niknafs, Hancocks, & Norton, 2013; Qian & McClements, 2011; Schultz, Wagner, Urban, & Ulrich, 2004; Yang, Leser, Sher, & McClements, 2013a). We therefore examined the influence of homogenization pressure on the droplet diameter of emulsions stabilized by gum arabic, corn fiber gum and beet pectin (Fig. 5). Overall, there was a decrease in mean droplet diameter (d_{43}) with increasing operating pressure for all of three emulsifiers, which can be attributed to an increase in the magnitude of the disruptive energy generated by the

homogenizer with increasing homogenization pressure (Schultz, et al., 2004). Over the range of pressures used (6.2×10^7 to 1.3×10^8 Pa), the mean droplet diameter changed from 0.82 to 0.65 μm , from 5.1 to 4.6 μm , and from 0.25 to 0.18 μm , for gum arabic, corn fiber gum and beet pectin, respectively. For all three polysaccharides, there was a linear decrease in the logarithm of the mean droplet diameter with the logarithm of the homogenization pressure (Fig. 5). This is in accordance with previous observations that there should be a linear relationship between homogenization pressure and droplet diameter as long as there is sufficient emulsifier present during homogenization (Walstra, 1993). The slopes determined from the $\text{Log}_{10}(d_{43})$ versus $\text{Log}_{10}(P)$ plots were around -0.34, -0.47, and -0.13 for gum arabic, beet pectin, and corn fiber gum respectively (Fig. 5), which is much lower than previously reported values of around -0.6 to -0.8 for high pressure homogenizers (Håkansson, Trägårdh, & Bergenståhl, 2009; Walstra, 2002). This result could have occurred for a number of reasons: (i) droplet breakup was not primarily governed by turbulent-inertial forces in the microfluidizer; (ii) the emulsifiers retarded droplet breakup; (iii) increasing droplet recoalescence occurred as the homogenization pressure was increased.

It should also be noted that the effects of emulsion viscosity on droplet breakup and coalescence within the homogenizer have not been taken into account. Emulsion viscosity depended on the type and amount of polysaccharide present in the aqueous phase, which may therefore have impacted the size of the droplets produced during homogenization (Walstra, 1993). However, polysaccharide solutions are highly shear thinning and therefore their viscosities may have been fairly similar to water at the very high shear rates generated within the microfluidizer at high operating pressures.

3.4. Influence of polysaccharides on emulsion stability

Emulsion stability is one of the most important factors determining the shelf life of many commercial products (Bai, et al., 2016a; Yang, Leser, Sher, & McClements, 2013b).

Furthermore, it provides a valuable indicator of the effectiveness of different emulsifiers at stabilizing emulsions. We therefore compared the storage stabilities of emulsions formed using different polysaccharides at ambient temperature (Fig. 6).

Initially, all of the emulsions had a homogeneous whitish appearance (Fig. 6). After 24 h storage, the gum arabic- and beet pectin-stabilized emulsions were still stable at all emulsifier concentrations. After 7 days storage, a visible cream layer formed on top of the emulsions containing 0.1 wt% gum arabic (Fig. 6a), while the other emulsions containing gum arabic were still stable, and there was no separation in any of the emulsions containing beet pectin (Fig. 6c). The relatively high stability of beet pectin-stabilized emulsion is mainly attributed to the fact that the creaming rate is proportional to the square of the droplet diameter, and so a reduction in droplet size decreases the rate of gravitational separation. Additionally, Brownian motion effects that favor a homogeneous distribution of droplets throughout the system counteract the gravitational forces when the droplets are sufficiently small (McClements, 2012). Furthermore, the high viscosity of the beet pectin emulsions could restrict the movement of the oil droplets, thereby providing more resistance to separation. The creaming observed in the gum arabic-stabilized emulsions at low polysaccharide concentration can be attributed to the relatively large droplet diameter and low emulsion viscosity.

The emulsions formed from corn fiber gum exhibited quite different behavior. Visible creaming was observed in these emulsions, particularly at intermediate and high polysaccharide levels after both 24 h and 7 days storage (Fig. 6b). The microstructure of the cream layer collected from the top of the corn fiber gum-stabilized emulsions containing 5 wt% polysaccharide was collected and observed by optical and confocal microscopy (Fig. 7). These images suggest that the oil droplets were highly flocculated and coalesced in these emulsions. The creaming observed in the emulsions containing corn fiber gum can be attributed to two effects: (i) the oil droplets were relatively large; (ii) depletion flocculation occurred at relatively high polysaccharide concentrations

(McClements, 2012). A schematic illustration of the depletion flocculation mechanism for corn fiber gum system is shown in Fig. 8. This phenomenon arises when droplet surfaces approach within a distance less than the mean diameter of the free corn fiber gum molecules in aqueous solution (Napper, 1983). The exclusion of the corn fiber gum molecules from the intervening gap is associated with an attractive inter-particle force, resulting from the tendency of water to flow out from the gap under the influence of the local osmotic pressure (Dickinson, 2003). Once the droplets are forced together due to this mechanism they become more susceptible to coalescence (McClements, 2015).

4. Conclusions

This study compared the emulsifying ability of different food-grade polysaccharides in fabricating oil-in-water emulsions using a microfluidization method. All of the polysaccharides were surface active, but exhibited significant differences in their interfacial characteristics. The effectiveness at lowering the interfacial tension decreased in the following manner: gum arabic $\geq$ beet pectin $>$ corn fiber gum.

Fine emulsions could be produced using all of the polysaccharide-based emulsifiers. However, gum arabic and beet pectin were much more effective at producing smaller droplet sizes at low emulsifier concentrations than corn fiber gum, with beet pectin being the most effective. This effect was attributed to three major differences between the emulsifiers: (i) the higher surface activity and lower surface load of gum arabic and beet pectin; (ii) the lower interfacial tension for gum arabic and beet pectin, and (iii) the smaller molecular weight of gum arabic and beet pectin. Emulsion viscosity increased with increasing polysaccharide concentration, especially for the beet pectin-stabilized emulsions, which may have been due to self-association of the beet pectin molecules. All three polysaccharides could be used to form emulsions from different food grade oils, and led to a decrease in mean droplet diameter with increasing homogenization pressure. The storage experiments indicated that the gum arabic- and beet pectin-stabilized emulsions

had good stability to droplet aggregation and gravitational separation mainly due to small oil droplet size and/or high emulsion viscosity. Conversely, the corn fiber gum-stabilized emulsions quickly separated into a cream layer at all emulsifier concentrations used, which was caused by the combination of larger oil droplet sizes and depletion flocculation. The results of this study provide valuable information for food and beverage manufacturers who would like to use natural emulsifiers within their products.

5. Acknowledgements

This material was also partly based upon research supported by the Cooperative State Research, Extension, Education Service, USDA, Massachusetts Agricultural Experiment Station (MAS00491) and USDA, NRI Grants (2013-03795), as well as by funding from DSM. Long Bai would like to thank the Chinese Scholarship Council for support. We thank Madhuvanti Kale and Z- Trim Holdings for kindly providing the corn fiber gum ingredient used in this study. We also thank Prof. Dr. Hans-Ulrich Endress and Herbstreith & Fox KG for kindly providing the sugar beet pectin used in this study. Finally, we thank TIC Gums for kindly providing the gum arabic used in the study.

References

- Bai, L., Huan, S., Gu, J., & McClements, D. J. (2016a). Fabrication of oil-in-water nanoemulsions by dual-channel microfluidization using natural emulsifiers: Saponins, phospholipids, proteins, and polysaccharides. *Food Hydrocolloids*, 61, 703-711.
- Bai, L., Liu, F., Xu, X., Huan, S., & McClements, D. J. (2017). Impact of polysaccharide molecular characteristics on viscosity enhancement and depletion flocculation. *Carbohydrate Polymers*, In Revision.
- Bai, L., & McClements, D. J. (2016b). Formation and stabilization of nanoemulsions using biosurfactants: Rhamnolipids. *Journal of Colloid and Interface Science*, 479, 71-79.
- Burapapadh, K., Kumpugdee-Vollrath, M., Chantasart, D., & Sriamornsak, P. (2010). Fabrication of pectin-based nanoemulsions loaded with itraconazole for pharmaceutical application. *Carbohydrate Polymers*, 82(2), 384-393.

- Castellani, O., Al-Assaf, S., Axelos, M., Phillips, G. O., & Anton, M. (2010a). Hydrocolloids with emulsifying capacity. Part 2-Adsorption properties at the n-hexadecane-Water interface. *Food Hydrocolloids*, 24(2-3), 121-130.
- Castellani, O., Al-Assaf, S., Axelos, M., Phillips, G. O., & Anton, M. (2010b). Hydrocolloids with emulsifying capacity. Part 2-Adsorption properties at the n-hexadecane-Water interface. *Food Hydrocolloids*, 24(2), 121-130.
- Chanamai, R., & McClements, D. (2001). Depletion flocculation of beverage emulsions by gum arabic and modified starch. *Journal of Food Science*, 66(3), 457-463.
- Charoen, R., Jangchud, A., Jangchud, K., Harnsilawat, T., Naivikul, O., & McClements, D. J. (2011). Influence of Biopolymer Emulsifier Type on Formation and Stability of Rice Bran Oil - in - Water Emulsions: Whey Protein, Gum Arabic, and Modified Starch. *Journal of Food Science*, 76(1), E165-E172.
- Chen, H., Qiu, S., Gan, J., Liu, Y., Zhu, Q., & Yin, L. (2016). New insights into the functionality of protein to the emulsifying properties of sugar beet pectin. *Food Hydrocolloids*, 57, 262-270.
- Cirre, J., Al-Assaf, S., Phillips, G. O., Yadav, M. P., & Hicks, K. B. (2014). Improved emulsification performance of corn fibre gum following maturation treatment. *Food Hydrocolloids*, 35, 122-128.
- De, S., Malik, S., Ghosh, A., Saha, R., & Saha, B. (2015). A review on natural surfactants. *RSC Advances*, 5(81), 65757-65767.
- Dickinson, E. (2003). Hydrocolloids at interfaces and the influence on the properties of dispersed systems. *Food Hydrocolloids*, 17(1), 25-39.
- Dickinson, E. (2015). Colloids in food: Ingredients, structure, and stability. *Annual Review of Food Science and Technology*, 6, 211-233.
- Funami, T., Nakauma, M., Ishihara, S., Tanaka, R., Inoue, T., & Phillips, G. O. (2011). Structural modifications of sugar beet pectin and the relationship of structure to functionality. *Food Hydrocolloids*, 25(2), 221-229.
- Funami, T., Zhang, G., Hiroe, M., Noda, S., Nakauma, M., Asai, I., Cowman, M. K., Al-Assaf, S., & Phillips, G. O. (2007). Effects of the proteinaceous moiety on the emulsifying properties of sugar beet pectin. *Food Hydrocolloids*, 21(8), 1319-1329.
- Gülseren, İ., & Corredig, M. (2014). Interactions between polyglycerol polyricinoleate (PGPR) and pectins at the oil-water interface and their influence on the stability of water-in-oil emulsions. *Food Hydrocolloids*, 34, 154-160.
- Håkansson, A., Trägårdh, C., & Bergenståhl, B. (2009). Dynamic simulation of emulsion formation in a high pressure homogenizer. *Chemical Engineering Science*, 64(12), 2915-2925.
- Hasenhuettl, G. L., & Hartel, R. W. (2008). *Food emulsifiers and their applications* (Vol. 19): Springer.
- Jafari, S. M., Assadpoor, E., He, Y., & Bhandari, B. (2008). Re-coalescence of emulsion droplets during high-energy emulsification. *Food Hydrocolloids*, 22(7), 1191-

1202.

Kokubun, S., Yadav, M. P., Moreau, R. A., & Williams, P. A. (2014). Components responsible for the emulsification properties of corn fibre gum. *Food Hydrocolloids*, 41, 164-168.

Kralova, I., & Sjöblom, J. (2009). Surfactants used in food industry: a review. *Journal of Dispersion Science and Technology*, 30(9), 1363-1383.

Lam, R. S. H., & Nickerson, M. T. (2013). Food proteins: A review on their emulsifying properties using a structure-function approach. *Food Chemistry*, 141(2), 975-984.

Lee, L. L., Niknafs, N., Hancocks, R. D., & Norton, I. T. (2013). Emulsification: Mechanistic understanding. *Trends in Food Science & Technology*, 31(1), 72-78.

Leroux, J., Langendorff, V., Schick, G., Vaishnav, V., & Mazoyer, J. (2003). Emulsion stabilizing properties of pectin. *Food Hydrocolloids*, 17(4), 455-462.

Li, X., Fang, Y., Al-Assaf, S., Phillips, G. O., Nishinari, K., & Zhang, H. (2009). Rheological study of gum arabic solutions: Interpretation based on molecular self-association. *Food Hydrocolloids*, 23(8), 2394-2402.

Maindarkar, S. N., Bongers, P., & Henson, M. A. (2013). Predicting the effects of surfactant coverage on drop size distributions of homogenized emulsions. *Chemical Engineering Science*, 89, 102-114.

McClements, D. J. (2004). Protein-stabilized emulsions. *Current Opinion in Colloid & Interface Science*, 9(5), 305-313.

McClements, D. J. (2007). Critical review of techniques and methodologies for characterization of emulsion stability. *Critical Reviews in Food Science and Nutrition*, 47(7), 611-649.

McClements, D. J. (2012). Nanoemulsions versus microemulsions: terminology, differences, and similarities. *Soft Matter*, 8(6), 1719-1729.

McClements, D. J. (2015). *Food Emulsions: Principles, Practices, and Techniques*: CRC press.

McClements, D. J., & Gumus, C. E. (2016). Natural emulsifiers—Biosurfactants, phospholipids, biopolymers, and colloidal particles: Molecular and physicochemical basis of functional performance. *Advances in Colloid and Interface Science*, 234, 3-26.

Nakauma, M., Funami, T., Noda, S., Ishihara, S., Al-Assaf, S., Nishinari, K., & Phillips, G. O. (2008). Comparison of sugar beet pectin, soybean soluble polysaccharide, and gum arabic as food emulsifiers. 1. Effect of concentration, pH, and salts on the emulsifying properties. *Food Hydrocolloids*, 22(7), 1254-1267.

Napper, D. H. (1983). *Polymeric stabilization of colloidal dispersions* (Vol. 3): Academic Pr.

Ngouemazong, E. D., Christiaens, S., Shpigelman, A., Van Loey, A., & Hendrickx, M. (2015). The Emulsifying and Emulsion - Stabilizing Properties of Pectin: A Review. *Comprehensive Reviews in Food Science and Food Safety*, 14(6), 705-718.

577 Ozturk, B., Argin, S., Ozilgen, M., & McClements, D. J. (2015). Formation and
578 stabilization of nanoemulsion-based vitamin E delivery systems using natural
579 biopolymers: whey protein isolate and gum arabic. *Food Chemistry*, 188, 256-263.

580 Ozturk, B., & McClements, D. J. (2016). Progress in natural emulsifiers for utilization in
581 food emulsions. *Current Opinion in Food Science*, 7, 1-6.

582 Pal, R. (2011). Rheology of simple and multiple emulsions. *Current Opinion in Colloid &*
583 *Interface Science*, 16(1), 41-60.

584 Phillips, G. O., & Williams, P. A. (2009). *Handbook of hydrocolloids*: Elsevier.

585 Qian, C., & McClements, D. J. (2011). Formation of nanoemulsions stabilized by model
586 food-grade emulsifiers using high-pressure homogenization: Factors affecting
587 particle size. *Food Hydrocolloids*, 25(5), 1000-1008.

588 Rao, J., & McClements, D. J. (2012). Food-grade microemulsions and nanoemulsions:
589 Role of oil phase composition on formation and stability. *Food Hydrocolloids*,
590 29(2), 326-334.

591 Reiner, S., Reineccius, G., & Peppard, T. (2010). A Comparison of the Stability of
592 Beverage Cloud Emulsions Formulated with Different Gum Acacia - and Starch
593 - Based Emulsifiers. *Journal of Food Science*, 75(5), E236-E246.

594 Rodríguez Patino, J. M., Rodríguez Niño, M. R., & Sánchez, C. C. (1999). Adsorption of
595 whey protein isolate at the oil-water interface as a function of processing
596 conditions: a rheokinetic study. *Journal of Agricultural and Food Chemistry*,
597 47(6), 2241-2248.

598 Sanchez, C., Renard, D., Robert, P., Schmitt, C., & Lefebvre, J. (2002). Structure and
599 rheological properties of acacia gum dispersions. *Food Hydrocolloids*, 16(3), 257-
600 267.

601 Schultz, S., Wagner, G., Urban, K., & Ulrich, J. (2004). High - pressure homogenization
602 as a process for emulsion formation. *Chemical Engineering & Technology*, 27(4),
603 361-368.

604 Siew, C. K., Williams, P. A., Cui, S. W., & Wang, Q. (2008). Characterization of the
605 surface-active components of sugar beet pectin and the hydrodynamic thickness
606 of the adsorbed pectin layer. *Journal of Agricultural and Food Chemistry*, 56(17),
607 8111-8120.

608 Tcholakova, S., Denkov, N. D., & Danner, T. (2004). Role of surfactant type and
609 concentration for the mean drop size during emulsification in turbulent flow.
610 *Langmuir*, 20(18), 7444-7458.

611 Vasile, F. E., Martinez, M. J., Ruiz-Henestrosa, V. M. P., Judis, M. A., & Mazzobre, M. F.
612 (2016). Physicochemical, interfacial and emulsifying properties of a non-
613 conventional exudate gum (*Prosopis alba*) in comparison with gum arabic. *Food*
614 *Hydrocolloids*, 56, 245-253.

615 Walstra, P. (1993). Principles of emulsion formation. *Chemical Engineering Science*,
616 48(2), 333-349.

617 Walstra, P. (2002). *Physical chemistry of foods*: CRC Press.

- Williams, P. A., & Phillips, G. O. (2009). Gum arabic. *Handbook of Hydrocolloids*, 2nd Edition(173), 252-273.
- Williams, P. A., Sayers, C., Viebke, C., Senan, C., Mazoyer, J., & Boulenguer, P. (2005). Elucidation of the emulsification properties of sugar beet pectin. *Journal of Agricultural and Food Chemistry*, 53(9), 3592-3597.
- Wooster, T. J., Golding, M., & Sanguansri, P. (2008). Impact of oil type on nanoemulsion formation and Ostwald ripening stability. *Langmuir*, 24(22), 12758-12765.
- Yadav, M. P., Hicks, K. B., Johnston, D., Hanah, K. A., Shukla, T. P., Yadav, M., Hicks, K., Hanah, K., & Shukla, T. (2014). Preparing bio-based fiber gums, used e.g. as emulsifiers to stabilize oil-in-water composition, comprises mixing agricultural materials with heated alkaline solution, separating out insoluble components from slurry, evaporating and drying. In (pp. 2872561-A2872561): US SEC OF AGRIC (USDA-C) US SEC OF AGRIC (USDA-C) Z TRIM HOLDINGS INC (ZTRI-Non-standard) Z TRIM HOLDINGS INC (ZTRI-Non-standard) US SEC OF AGRIC (USDA-C) US SEC OF AGRIC (USDA-C) Z TRIM HOLDINGS INC (ZTRI-Non-standard) Z-TRIM HOLDINGS INC (ZTRI-Non-standard).
- Yadav, M. P., Johnston, D. B., & Hicks, K. B. (2007a). Structural characterization of corn fiber gums from coarse and fine fiber and a study of their emulsifying properties. *Journal of Agricultural and Food Chemistry*, 55(15), 6366-6371.
- Yadav, M. P., Johnston, D. B., & Hicks, K. B. (2009). Corn fiber gum: New structure/function relationships for this potential beverage flavor stabilizer. *Food Hydrocolloids*, 23(6), 1488-1493.
- Yadav, M. P., Johnston, D. B., Hotchkiss, A. T., & Hicks, K. B. (2007b). Corn fiber gum: A potential gum arabic replacer for beverage flavor emulsification. *Food Hydrocolloids*, 21(7), 1022-1030.
- Yadav, M. P., Parris, N., Johnston, D. B., & Hicks, K. B. (2008). Fractionation, characterization, and study of the emulsifying properties of corn fiber gum. *Journal of Agricultural and Food Chemistry*, 56(11), 4181-4187.
- Yadav, M. P., Parris, N., Johnston, D. B., Onwulata, C. I., & Hicks, K. B. (2010). Corn fiber gum and milk protein conjugates with improved emulsion stability. *Carbohydrate Polymers*, 81(2), 476-483.
- Yadav, M. P., Strahan, G. D., Mukhopadhyay, S., Hotchkiss, A. T., & Hicks, K. B. (2012). Formation of corn fiber gum–milk protein conjugates and their molecular characterization. *Food Hydrocolloids*, 26(2), 326-333.
- Yang, Y., Leser, M. E., Sher, A. A., & McClements, D. J. (2013a). Formation and stability of emulsions using a natural small molecule surfactant: Quillaja saponin (Q-Naturale (R)). *Food Hydrocolloids*, 30(2), 589-596.
- Yang, Y., Leser, M. E., Sher, A. A., & McClements, D. J. (2013b). Formation and stability of emulsions using a natural small molecule surfactant: Quillaja saponin (Q-Naturale®). *Food Hydrocolloids*, 30(2), 589-596.
- Zhang, F., Luan, T., Kang, D., Jin, Q., Zhang, H., & Yadav, M. P. (2015a). Viscosifying

659 properties of corn fiber gum with various polysaccharides. *Food Hydrocolloids*,
 660 43, 218-227.
 661 Zhang, J., Bing, L., & Reineccius, G. A. (2016). Comparison of modified starch and
 662 Quillaja saponins in the formation and stabilization of flavor nanoemulsions.
 663 *Food Chemistry*, 192, 53-59.
 664 Zhang, L., Shi, Z., Shangguan, W., Fang, Y., Nishinari, K., Phillips, G. O., & Jiang, F.
 665 (2015b). Emulsification properties of sugar beet pectin after modification with
 666 horseradish peroxidase. *Food Hydrocolloids*, 43, 107-113.
 667

Figure captions

Fig.1. Influence of gum arabic, corn fiber gum, and beet pectin concentrations on the interfacial tension measured at the corn oil-water interface.

Fig.2. (a) Influence of gum arabic, corn fiber gum and beet pectin concentrations on the mean particle diameter (d_{43}) of 10 wt% corn oil-in-water emulsions. Particle size distributions of emulsions containing different concentrations of (b) gum arabic, (c) corn fiber gum, and (d) beet pectin. All the emulsions were produced by standardized homogenization conditions (13 kpsi, three cycles). The data is shifted up the y-axis to facilitate comparison of different samples.

Fig.3. Influence of gum arabic, corn fiber gum and beet pectin concentrations on the emulsion viscosity of 10 wt% corn oil-in-water emulsions. The tested temperature was 25 °C. All the emulsions were produced by standardized homogenization conditions (13 kpsi, three cycles).

Fig.4. Influence of gum arabic, corn fiber gum and beet pectin on the mean particle diameter (d_{43}) of 10% oil-in-water emulsions with different oil types produced by standardized homogenization condition (13 kpsi, three cycles). The concentrations of gum arabic, corn fiber gum, and beet pectin were 5 wt%, 5 wt% and 2 wt%, respectively.

Fig.5. Influence of homogenization pressure on the mean particle diameter (d_{43}) of 10 wt% corn oil-in-water emulsions containing (a) 5 wt% gum arabic and 2 wt% beet pectin, and (b) 5 wt% corn fiber gum produced by standardized homogenization condition (three cycles at different pressures).

Fig.6. Visual appearance of emulsions stabilized by different concentrations of (a) gum arabic, (b) corn fiber gum, and (c) beet pectin. Upper photos represented the emulsions at Day-0, middle photos represented the emulsion at Day-1, and lower photos represented the emulsions at Day-7. All the emulsions were stored at room temperature.

Fig.7. (a) optical and (b) confocal micrographs of the top cream layer of corn oil-in water emulsion stabilized by 5 wt% corn fiber gum. The magnification of (a) is 40×, and the magnification of (b) is 60×. The oil phase in (b) was stained by Nile red prior observation.

Fig.8. Schematic illustration of depletion flocculation of oil droplets in the corn fiber gum-stabilized emulsions with excess non-adsorbed biopolymer molecules reaching the critical flocculation concentration.

Fig.1.

Fig.2.

Fig.3.

Fig.4.

Fig.5.

Fig.6.

Fig.7.

Fig.8.

Table 1 The refractive indices (RI) of water and different oil type used in this study. ^a

Phase	RI
Water	1.330
MCT	1.445
Corn oil	1.472
Fish oil	1.481
Lemon oil (10-fold)	1.487
Lemon oil (3-fold)	1.475

^a The RI of the oils was measured at ambient temperature (25 °C).

Supplementary material for

Emulsifying properties of food-grade polysaccharides in oil-in-water emulsions: Gum arabic, beet pectin, and corn fiber gum

Long Bai^{a,b}, Siqi Huan^a, Zhiguo Li^{*a}, David Julian McClements^{*b,c}

^a College of Material Science and Engineering, Northeast Forestry University, Harbin 150040, PR China

^b Biopolymers and Colloids Laboratory, Department of Food Science, University of Massachusetts, Amherst, MA 01003, USA

^c Department of Biochemistry, Faculty of Science, King Abdulaziz University, P. O. Box 80203 Jeddah 21589 Saudi Arabia

Figure S1. Influence of emulsifier type and concentration on the surface pressure at corn oil-water interfaces containing gum arabic, corn fiber gum and beet pectin.