Carbohydrate Polymers 111 (2014) 624–632

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Stability and physicochemical properties of model salad dressings prepared with pregelatinized potato starch

Grażyna Bortnowska[a,*], Jerzy Balejko[b], Violetta Schube[c], Grzegorz Tokarczyk[a], Natalia Krzemińska[a], Katarzyna Mojka[a]

[a] Department of Food Technology, West Pomeranian University of Technology in Szczecin, Poland
[b] Department of Food Process Engineering, West Pomeranian University of Technology in Szczecin, Poland
[c] Ingredion GmbH, Hamburg, Germany

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 12 April 2014
Accepted 6 May 2014
Available online 17 May 2014

Keywords:
Salad dressings
Potato starch
Physicochemical properties
Sensory evaluation

ABSTRACT

The effects of pregelatinized potato starch concentration (PSC) ranged from 0 to 5 wt% on the physical stability, color, rheological, textural, and sensory properties of model salad dressings prepared with 2 wt% dried egg yolk (DEY) or sodium caseinate (SC) were explored. All dressings showed shear-thinning behavior with yield stress. Raising PSC increased storage (G') and loss (G'') moduli decreasing loss tangent ($\tan\delta$) and samples containing ≥3 wt% starch showed a weak gel-like ($\tan\delta < 1$) response. A generalized Cox–Merz rule was applicable to indicate shear/strain sensitivity of the dressings structures. Rheological characterization based on Bohlin's parameters (A, z) was useful for distinguishing physical stability of dressings made with different formulations. Changes in color were generally very small and mainly PSC-dependent. Correlation analyses revealed that sensory descriptors could be satisfactory modeled with the appropriate instrumental data. Overall, the results proved that pregelatinized potato starch may be suitable ingredient in low-fat dressings applications.

1. Introduction

Commercial salad dressings are oil-in-water (o/w) emulsions frequently used by the food industry to enhance the attractiveness and tastiness of different products. These systems are thermodynamically unstable, and the instability is particularly accelerated, when the fat content is reduced below 60–65% (Drakos & Kiosseoglou, 2008; Ma, Boye, Fortin, Simpson, & Prasher, 2013). Physical stability of dressings can be extended for reasonable period of time, creating kinetic barriers to droplets coalescence by applying effective emulsifiers and thickeners/stabilizers (Bortnowska, Krzemińska, & Mojka, 2013; Dickinson, 2003).

Hen egg yolk (EY) is a key ingredient in a wide variety of food emulsions, as it combines excellent emulsifying properties and appreciated organoleptic characteristics (Laca, Sáenz, Paredes, & Díaz, 2010). Native EY consists of mixtures of lipids and proteins noncovalently bound in the form of large lipoprotein complexes, which confer on EY a high emulsifying capacity. However, EY in native form is not microbiologically stable, therefore spray-drying as the preservative process is commonly used to ensure longer stability of final product (Moros, Franco, & Gallegos, 2002). Sodium caseinate (SC) is a heterogeneous mixture of disordered amphiphilic proteins (α_{s1}-, α_{s2}-, β- and κ-) having ability for rapidly conferring a low interfacial tension during emulsification (Farshchi, Ettelaie, & Holmes, 2013; Huck-Iriart, Álvarez-Cerimedo, Candal, & Herrera, 2011). SC can easily create films from aqueous solutions because of its random coil nature and ability to form extensive intermolecular hydrogen, electrostatic and hydrophobic bonds, resulting in an increase of the interchain cohesion (Khwaldia, Banon, Perez, & Desobry, 2004). Starch is made up of two polymers of D-glucose: amylose, an essentially unbranched $\alpha[1\rightarrow4]$ linked glucan and amylopectin, which has chains of $\alpha[1\rightarrow4]$ linked glucoses arranged in a highly branched structure with $\alpha[1\rightarrow6]$ branching links (Copeland, Blazek, Salman, & Tang, 2009). This hydrocolloid is a major source of carbohydrates in the human diet and widely used in the food industry as a thickening and stabilizing agent (Dolz, Hernández, & Delegido, 2006). Over the last few decades, starch has been modified to improve its properties and tolerance to processing conditions. Physical modification (e.g. pregelatinization) of starch can be safely used because it does not involve any chemical presence (Kaur, Ariffin, Bhat, & Karim, 2012).

The interactions between components of food-grade emulsifiers and polysaccharides can be either detrimental or beneficial and

* Corresponding author. Tel.: +48 91 449 6526; fax: +48 91 449 6532.
E-mail address: Grazyna.Bortnowska@zut.edu.pl (G. Bortnowska).

http://dx.doi.org/10.1016/j.carbpol.2014.05.015
0144-8617/

this greatly affects properties of final product (Dickinson, 2003). Previously, we found that application of pregelatinized waxy maize starch allowed to develop cold prepared food emulsions with a very wide range of textural and rheological properties (Bortnowska, Balejko, Tokarczyk, Romanowska-Osuch, & Krzemińska, 2014). However, the effects of pregelatinized starches containing higher amylose/amylopectin ratios than waxy-type ones on the physicochemical characteristics of salad dressings have not been well evidenced.

The objective of the present work was to examine the influence of pregelatinized potato starch concentration on the stability, physicochemical and sensory properties of low-fat salad dressings prepared with dried egg yolk and sodium caseinate.

2. Materials and methods

2.1. Materials and reagents

Spray-dried sodium caseinate (91.2 wt% protein, 1.8 wt% lipids, 4.8 wt% moisture) and dried egg yolk (33.1 wt% protein, 56.7 wt% total lipids having 28.4 wt% phospholipids, and 3.9 wt% moisture) were purchased from Duncean (Kamień Pomorski, Poland). Pregelatinized potato starch, Novation® 6600 (20 wt% amylose) was donated by Ingredion (Hamburg, Germany). Rapeseed oil (7 wt% saturated, 65 wt% monounsaturated and 28 wt% polyunsaturated fatty acids) was bought from a local retailer. Analytical grade: potassium sorbate, hydrochloric acid (HCl), and sodium hydroxide (NaOH) were obtained from Hartim (Szczecin, Poland). Double-distilled water was used to prepare all solutions, and dressings. Composition of the ingredients is reported as stated by the producers.

2.2. Model salad dressings preparation

Aqueous phases were prepared by dispersing dried egg yolk (DEY), sodium caseinate (SC) and potato starch (PS) in double-distilled water with addition of potassium sorbate, followed by stirring at room temperature overnight to ensure complete dispersion and hydratation. The oil-in-water emulsions were manufactured by homogenizing (1 min, 14 000 rpm) the aqueous mixtures of DEY and SC with rapeseed oil, using a laboratory-scale MPW 302 homogenizer (Mechanika Precyzyjna, Warszawa, Poland). The model salad dressings were produced by mixing (speed 8, 2 min) emulsion samples with the aqueous solutions of PS using a K4555 kitchen robot (KitchenAid, St. Joseph, MI, USA). The pH of the dressings was adjusted to 7.0 with 0.1 M HCl or 0.1 M NaOH. Finally the dressings contained 20 wt% rapeseed oil, 2 wt% DEY or SC, 0.1 wt% potassium sorbate and PS ranged from 0 to 5 wt%. The control samples were prepared at the same procedures without adding PS. All experiments were carried out at a fixed temperature of $22 \pm 0.5\,^{\circ}$C.

2.3. Stability test

Stability of salad dressings to creaming (ESC) and fat holding capacity (FHC) was determined after accelerated ageing. Aliquots (~8.0 mL) of the dressings were transferred to the 10 mL test tubes which were tightly sealed with plastic caps and then centrifuged at $2400 \times g$ for 15 min, using a MPW 350 centrifuge (Med.-Instruments, Warszawa, Poland). The ESC parameter was derived from the relation: ESC (%) = $(H_C/H_T) \times 100$, where: H_C, the height of the creamed layer and H_T, the total height of emulsion, whereas, the FHC one was calculated as follows: FHC (%) = $(V_R/V_A) \times 100$, where: V_R, oil volume remained in the dressing system after centrifugation and V_A, oil volume added to the sample during its formation.

2.4. Color assessment

Color of the salad dressings was measured with a HunterLab Model D25-2A Digital Color Difference Meter (Hunter Associates Laboratory Inc., Fairfax, VA, USA) at 2° view angle. The calibration was done with a white C2-6544 plate (X = 86.30, Y = 88.51, Z = 101.99). Color coordinates were expressed as lightness (L^*), redness/greenness (+/−a^*) and yellowness/blueness (+/−b^*). Experimental data were characterized in terms of colour distance: $\Delta E_{a^*b^*} = [L^{*2} + a^{*2} + b^{*2}]^{1/2}$, whiteness index: $\mathrm{WI} = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{1/2}$, hue angle: $H^\circ = tg^{-1}(b^*/a^*)$ and total color difference: $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ where: ΔL^*, Δa^* and Δb^* are differences between the adequate color parameters of the containing PS and control samples.

2.5. Texture profile analysis

The texture profile analysis (TPA) was performed according to Bortnowska et al. (2014) using a back-extrusion (pseudo-compression) test on a Texture Analyzer model TA-XT2 (Stable Micro Systems Ltd., Surrey, UK) equipped with back extrusion cell (A/BE), 5 kg load cell, and 45 mm compression plate diameter. The force-time forces were analyzed using Texture Expert® for Windows® v. 1.11 equipment software and the determined parameters were firmness (N), consistency (N s), cohesiveness (N) and adhesiveness (N s).

2.6. Determination of rheological properties

Rheological properties of salad dressings were conducted using a strain/stress controlled AR 2000ex rheometer (TA Instruments, New Castle, DE, USA) equipped with a cone-plate configuration (1° cone angle, 40 mm diameter, 26 μm gap) and a Peltier temperature controlling system. All dressing samples were allowed to rest for 5 min after loading to allow temperature equilibration and induced stress to relax. Steady-state flow measurements were carried out in the range of 1–600 s^{-1} and the rheological parameters were obtained from the TA Rheology Advantage Data Analysis equipment software V 5.4.7. Experimental flow curves were fitted to the Herschel–Bulkley (H–B) model: $\sigma = \sigma_0 + K \cdot \dot{\gamma}^n$, where: σ, shear stress (Pa); σ_0, yield stress (Pa); K, consistency coefficient (Pa s^n); $\dot{\gamma}$, shear rate (s^{-1}) and n, flow behavior index (–). The effective viscosity: $\eta_{\mathrm{eff}}(\mathrm{Pa\,s}) = \sigma_0/\dot{\gamma} + K\dot{\gamma}^{n-1}$ for the H–B model was calculated at $\dot{\gamma} = 100\,\mathrm{s}^{-1}$. Dynamic oscillatory test was performed over an angular frequency (ω) range of 1–50 rad/s within linear viscoelastic region at constant shear stress of 0.6 Pa. Storage (elastic) modulus (G', Pa), loss (viscous) modulus (G'', Pa), complex modulus: G^* (Pa) = $(G'^2 + G''^2)^{1/2}$, loss tangent: $\tan\delta = G''/G'$, and complex viscosity: η^* (Pa s) = G^*/ω, were thus obtained as a function of ω. The plateau modulus: G_N^0 (Pa) = $[G']_{\tan\delta \to \mathrm{minimum}}$ was determined as described by Ma et al. (2013). The G', G'' and η^* parameters were modeled as power functions using following expressions: $G' = K'\,\omega^{n'}$, were thus obtained as a function of $G'' = K''\omega^{n''}$, and $\eta^* = K^*\omega^{n^*-1}$, where: K', K'', K^* (Pa $\mathrm{s}^{n'}$, Pa $\mathrm{s}^{n''}$, Pa s^{n^*}) and n', n'', n^* (–), are consistency coefficients and behavior indexes, respectively. Relationship between the steady-state shear and oscillatory data was established using a generalized Cox–Merz rule: $\eta^*(\omega) = k\{[\eta_a(\dot{\gamma})]^{\beta}\}_{\omega=\dot{\gamma}}$, where: η_a, apparent viscosity (Pa s) and k, β, constants. The Bohlin's parameters were assessed from the equation: $G^* = A\omega^{1/z}$, where: z, coordination number (dimensionless) and A, proportional coefficient (Pa $\mathrm{s}^{1/z}$) (Manoi & Rizvi, 2009).

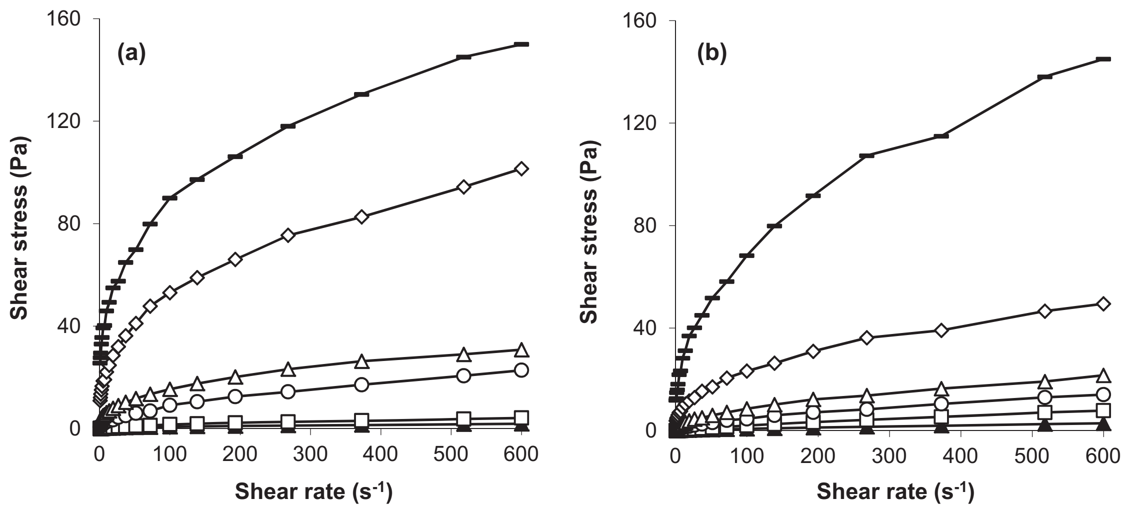

Fig. 1. Flow curves of salad dressings stabilized by dried egg yolk (a) and sodium caseinate (b) at different potato starch (PS) concentration (▲) Control; (□) 1 wt% PS; (○) 2 wt% PS; (△) 3 wt% PS; (◊) 4 wt% PS; (–) 5 wt% PS.

2.7. Sensory evaluation

Sensory evaluation was performed by a trained panel consisting of 16 assessors from Food Technology Department at West Pomeranian University of Technology in Szczecin, Poland. The samples were rated for: flowability (flow tendency when cup is slowly tipped), firmness (force required to compress the dressing using 45 mm plate), consistency (while pouring the dressing from spoon), cohesiveness (resistance to withdrawal from the dressing 45 mm plate) and adhesiveness (removal/slipping off of the dressing from a plastic spoon when it is slowly tipped at an angle of 45°) (Pereira, Singh, Munro, & Luckman, 2003). The pots filled with 100 mL dressing samples were labeled with three-digit random numbers and presented to panelists in triplicate. A nine-point scale in which the scores 1 and 9 corresponded to the lowest and highest ratings, respectively was used. The relationship between sensory perception (S), by testing dressing samples in the mouth and product rheology (P) was established, using modified Stevens equation: $S = S_0 P^{\alpha}$, where: S_0, proportionality constant and α, characteristic quantity for a given attribute–property relationship (Laca et al., 2010).

2.8. Statistical analysis

All analyses were performed in triplicate and data were subjected to two-way analysis of variance with interaction (ANOVA) using the software Statistica 6.0 (StatSoft, Kraków, Poland). Significant differences between means were determined by Tukey's multiple comparison tests at $p < 0.05$. Pearson correlation test was conducted to determine the relationships among variables. The effects of PSC on selected parameters were tested using exponential: $y = a\exp^{bx}$ and quadratic polynomial: $y = ax^2 + bx + c$ models to obtain the maximum values of R^2 coefficients.

3. Results and discussion

3.1. Rheological characterization

3.1.1. Flow behavior

The flow curves (shear stress vs. shear rate) of the explored salad dressings are presented in Fig. 1a and b. Overall, both sets of samples, i.e. stabilized by dried egg yolk (DEY) or sodium caseinate (SC), demonstrated fairly similar rheological behavior and trends with the shear stress increasing with raising shear rate (or apparent viscosity decreasing with increasing shear rate – data not shown). This generally is in good accordance with our previous findings regarding sauces made with starches differing in amylose/amylopectin ratios (Bortnowska, Krzemińska, & Mojka, 2013) and may be explained as the result of disentanglement of the polymer chains under shear, progressive deformation and the alignment of the particles in the direction of flow (Mun et al., 2009; Utrilla-Coello et al., 2014). Irrespectively of the applied emulsifier type (ET), increasing potato starch concentration (PSC) caused an upward shift of the flow curves. This likely may be attributed to the growing resistance to shearing forces due to the formation of stronger gel held together by intermolecular interactions involving amylose and amylopectin molecules (Copeland et al., 2009; Singh, Singh, Kaur, Sodhi, & Gill, 2003). Moreover, generation of complexes as a result of electrostatic and weak hydrophobic interactions between starch, protein and lipid molecules should be considered as well (Huck-Iriart et al., 2011; Shah, Zhang, Hamaker, & Campanella, 2011). It has been also observed that in majority at given shear rate, dressings formulated with DEY (Fig. 1a) demonstrated higher values of shear stress (apparent viscosity) than adequate ones made with SC (Fig. 1b). This generally is opposite to the results that we found examining emulsions made with waxy maize starch (WMS) (Bortnowska et al., 2014) and may be related to the variations in functional properties of the applied starches (Utrilla-Coello et al., 2014; Xie et al., 2009). Potato starch (PS) used in the current experiment contained amylose which has been reported that form inclusion complexes with lipids such as fatty acids, phospholipids and monoacylglycerides (Ahmadi-Abhari, Woortman, Hamer, Oudhuis, & Loos, 2013; López, de Vries, & Marrink, 2012). Hence, it may be hypothesized that intergranular network composed of amylose-inclusion complexes based on DEY lipids, intertwined with amylopectin may have contributed to the observed differences of apparent viscosity between DEY-than SC-stabilized dressings (Chang, He, & Huang, 2013; Putseys, Lamberts, & Delcour, 2010). To identify the flow characteristics of dressings, data from steady-state measurements were fitted to the Herschel–Bulkley (H–B) equation ($R^2 > 0.991$) and the associated parameters, including calculated for this model effective viscosity (η_{eff}) are summarized in Table 1. All systems demonstrated yield stress (σ_0), which is perceived to be particularly very important for salad dressings because it allows to retain their ability to adhere to salad surfaces (Liu, Xu, & Guo, 2007). ANOVA revealed that ET, PSC and ET × PSC interaction significantly ($p < 0.001$) affected H–B and η_{eff} parameters. Moreover, as reflected by higher F values,

Table 1
Rheological parameters of salad dressings based on Herschel–Bulkley model.

	DEY-stabilized salad dressings						SC-stabilized salad dressings					
	PS (wt%)											
	0	1	2	3	4	5	0	1	2	3	4	5
σ_0 (Pa)	0.01a	0.01a	0.09a	0.55b	1.73c	8.47e	0.02a	0.03a	0.13a	0.14a	0.60b	2.28d
K (Pa s^n)	0.06a	0.14a	0.73b	2.30c	8.92e	17.3g	0.02a	0.05a	0.26a	0.78b	3.08d	9.35f
n (–)	0.53a	0.53a	0.53a	0.41b	0.38bc	0.33c	0.79d	0.78d	0.62e	0.52a	0.43b	0.43b
η_{eff} (Pa s)	0.01a	0.02a	0.09b	0.15c	0.52e	0.87g	0.01a	0.02a	0.05ab	0.08b	0.23d	0.69f

For the definition of abbreviations, see Section 2. Within the rows, values followed by different letters are significantly different ($p < 0.05$).

PSC was the most influential factor exerted changes of η_{eff}, σ_0 and consistency coefficient (K), whereas flow behavior index (n) was mostly affected by ET. In both examined sets of samples, the σ_0, K and η_{eff} tended to increase with raising PSC and opposite effects were observed regarding n values. The results of the regressions between selected H-B parameters and PSC are summarized in Table 2. At PSC ≥ 3 wt% the corresponding values of σ_0, K and η_{eff} were significantly ($p < 0.05$) higher in DEY- than SC-stabilized dressings (Table 1). Opposite effects regarding σ_0 and K values were detected in our previous study (Bortnowska et al., 2014). Moreover, adequate samples made with WMS (former study) yielded in majority greater n values than those examined currently. This may be related to differences in amylose content, because this component was found to increase entanglements between chains with raising its concentration, whereas highly branched amylopectin is generally not expected to form effective entanglements (Xie et al., 2009). It should be also highlighted, that in dressings formulated with DEY (PSC ≥ 4 wt%) and SC (PSC = 5 wt%) the K values were comparable to those found in full-fat mayonnaises, whereas the σ_0 ones were much smaller (Liu et al., 2007), assumably due to the lower strength of attractive forces and weaker network structure (Gamonpilas et al., 2011; Udomrati, Ikeda, & Gohtani, 2013).

3.1.2. Viscoelastic properties

Dynamic oscillatory shear test was used to characterize viscoelastic properties of salad dressings and the determined G' and G'' moduli are shown in Fig. 2a–d. The G' modulus is a measure of the energy stored in the material and recovered from it per cycle of sinusoidal shear deformation, whereas the G'' one is an estimate of energy dissipated as heat per cycle (Singh et al., 2003). Irrespectively, of the applied ET and PSC, the G' and G'' demonstrated ascending tendency with increasing oscillation frequency (ω), however the impact of ω was higher in dressings containing ≤2 wt% than ≥3 wt% PS. Both studied moduli were shifted to higher values with raising PSC, and throughout the frequency range, the G'' dominated over G' when PSC was ≤2 wt%, whereas opposite effects were found at PSC ≥ 3 wt%. An explanation for these results is that higher thickener concentration could favor specific chain-chain associations and/or entanglements between polymer chains enhancing the density of cross-links (Mancini, Montanari, Peressini, & Fantozzi, 2002). Moreover, as shown in Table 3, DEY-stabilized dressings containing ≥3 wt% PS yielded generally ($p < 0.05$) higher values of plateau modulus (G_N^0) than adequate ones made with SC. The G_N^0 values were also considerably ($p < 0.001$) correlated with those of σ_0 in both examined systems. The G_N^0 is a viscoelastic parameter defined for polymers as the extrapolation of the entanglement contribution to the viscoelastic functions at high frequencies (Lorenzo, Checmarev, Zaritzky, & Califano, 2011). It can be therefore asserted that dressings made with DEY yielded stronger emulsion network than those prepared with SC (Ma et al., 2013; Udomrati et al., 2013). Loss tangent (tan δ) was used to explain whether elastic or viscous properties predominate in the dressing samples (Fig. 3a and b). Irrespectively of the applied ET, in samples containing ≤2 wt% PS, the values of tan δ were >1 and the curves showed declining trend over the frequency range considered. This may suggest that the intermolecular interactions were very weak and the droplets network structure could easily rearrange to accommodate the strain (Diftis, Biliaderis, & Kiosseoglou, 2005). Therefore, it could be concluded that these dressings behaved like liquids and the energy used to deform the material was partly viscously dissipated as heat (Bortnowska et al., 2014). In contrast, in systems containing ≥3 wt% PS ascending trend of tan δ was found and the values throughout the tested frequency range were <1. This shows that these dressings had a structure like weak gel (tan δ > 0.1) and the deformation

Table 2
Results of the regressions between selected parameters and potato starch concentration.

Parameters	Function	DEY-stabilized salad dressings				SC-stabilized salad dressings			
		Function parameters							
		a	b	c	R^2	a	b	c	R^2
σ_0	Exponential	0.0054	1.4565	–	0.9695	0.0151	0.9355	–	0.9578
K	Exponential	0.057	1.198	–	0.9894	0.0181	1.2628	–	0.9963
K'	Quadratic	13.075	−32.688	7.8329	0.9845	–	–	–	–
	Exponential	–	–	–	–	0.0068	1.9401	–	0.9920
K''	Quadratic	1.4393	−2.827	0.5757	0.9929	–	–	–	–
	Exponential	–	–	–	–	0.0348	1.2900	–	0.9983
Firmness	Quadratic	0.1048	−0.2478	0.2454	0.9778	0.0377	−0.085	0.1981	0.9680
$\Delta E_{a^*b^*}$	Quadratic	0.1513	0.9226	76.16	0.9937	−0.0404	0.8818	88.722	0.9941
ESC	Exponential	18.516	0.3682	–	0.9680	19.617	0.3389	–	0.9591
A	Quadratic	13.091	−32.513	7.8427	0.9848	–	–	–	–
	Exponential	–	–	–	–	0.0259	1.646	–	0.9917
z	Quadratic	0.2197	0.4158	1.0974	0.9113	0.3645	−0.3893	1.0787	0.9024

For the definition of abbreviations, see Section 2.

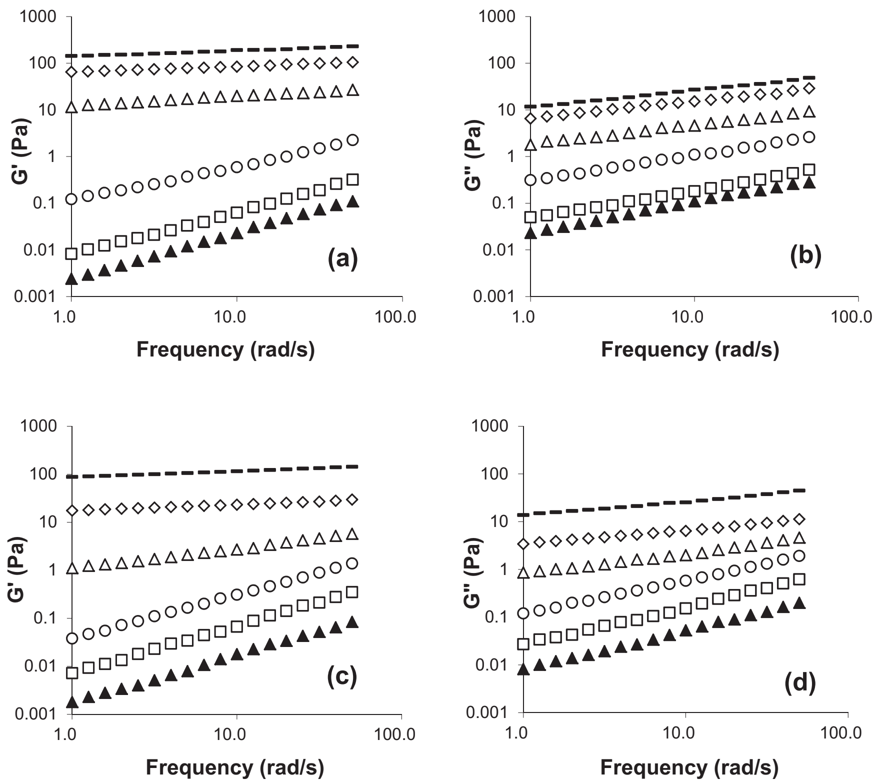

Fig. 2. Storage modulus (G') and loss modulus (G'') rheograms versus frequency for salad dressings, formulated with dried egg yolk (a, b) and sodium caseinate (c, d) at different potato starch (PS) concentration (▲) Control; (□) 1 wt% PS; (◯) 2 wt% PS; (Δ) 3 wt% PS; (◊) 4 wt% PS; (–) 5 wt% PS.

Table 3
Plateau modulus ($G_N^0 = [G']_{\tan\delta \to \text{minimum}}$) and parameters of power law model for storage and loss moduli ($G' = K'\omega^{n'}$, $G'' = K''\omega^{n''}$), complex viscosity ($\eta^* = K^*\omega^{n^*-1}$) and generalized Cox–Merz rule ($\eta^*(\omega) = k\{[\eta_a(\dot{\gamma})]^{\beta}\}_{\dot{\gamma}=\omega}$).

	DEY-stabilized salad dressings						SC-stabilized salad dressings					
	PS (wt%)											
	0	1	2	3	4	5	0	1	2	3	4	5
G_N^0 (Pa)	0.11a	0.32a	2.25a	11.5b	64.9d	144f	0.08a	0.35a	1.39a	1.24a	17.5c	88.5e
K' (Pa s$^{n'}$)	0.02a	0.04a	0.44a	17.6b	80.7d	177f	0.01a	0.04a	0.20a	2.31a	22.0c	110e
n' (–)	0.99a	0.94b	0.74c	0.21d	0.12f	0.12f	0.99a	0.99a	0.92b	0.42e	0.13f	0.12f
K'' (Pa s$^{n''}$)	0.08a	0.14a	0.82b	3.87c	12.9e	22.4g	0.04a	0.11a	0.43ab	1.76d	5.82f	23.3h
n'' (–)	0.65a	0.60b	0.54c	0.41fg	0.37g	0.36g	0.82d	0.80d	0.71e	0.43f	0.30h	0.29h
K^* (Pa s$^{n^*}$)	0.08a	0.15a	0.94a	18.1c	81.9e	178g	0.04a	0.12a	0.47a	2.91b	22.8d	113f
n^*(–)	0.67a	0.63ab	0.59b	0.22e	0.13g	0.13g	0.84c	0.83c	0.75d	0.42f	0.14g	0.13g
k	1.26c	0.67b	1.23c	5.26e	5.98h	4.55f	0.18a	0.24a	0.79b	3.01d	4.26g	5.14e
β	0.96d	0.75c	0.90d	1.17e	1.11e	1.15e	0.44b	0.29a	0.50b	0.99d	1.30f	1.29f

For the definition of abbreviations, see Section 2. Within the rows, values followed by different letters are significantly different ($p < 0.05$).

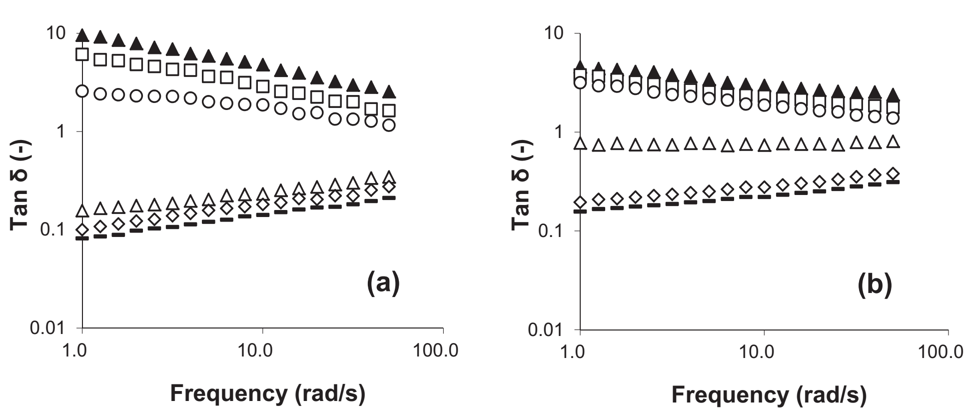

Fig. 3. Loss tangent (tan δ) of salad dressings prepared with dried egg yolk (a) and sodium caseinate (b) at different potato starch (PS) concentration (▲) Control; (□) 1 wt% PS; (◯) 2 wt% PS; (Δ) 3 wt% PS; (◊) 4 wt% PS; (–) 5 wt% PS.

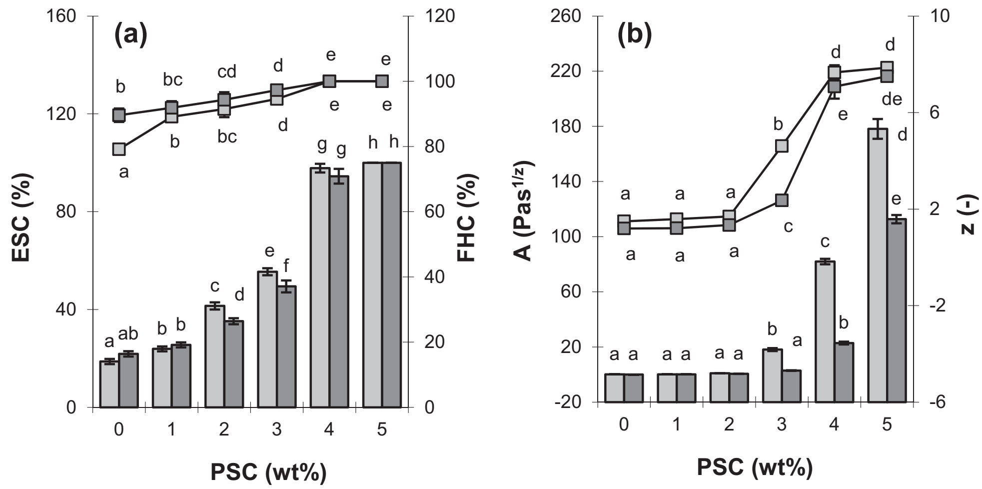

Fig. 4. Effects of potato starch concentration (PSC) on physical stability parameters (a): creaming – ESC (columns), fat holding capacity – FHC and Bohlin's parameters (b): proportional coefficient – *A* (columns), coordination number – *z* of salad dressings prepared with dried egg yolk (DEY) and sodium caseinate (SC). Mean values (within the same parameters) marked with no common letters are significantly different ($p < 0.05$). (▲) DEY; (□) SC; (○) DEY; (△) SC.

in the linear range will be essentially elastic or recoverable (Lorenzo et al., 2011; Ma et al., 2013). The G', G'' moduli and η^* were modeled as a power function ($R^2 > 0.9836$) of ω and the obtained values are summarized in Table 3. ANOVA revealed that ET, PSC, and their interaction significantly ($p < 0.001$) affected K', K'', K^* and n', n'', n^* parameters with PSC as the most influential factor. The functions used for modeling the K' and K'' are shown in Table 2. None of the dressing samples exhibited superposition of apparent (η_a) and complex (η^*) viscosities, therefore the generalized Cox–Merz (GC-M) rule was applied to compare the steady and oscillatory shear measurements (Gamonpilas et al., 2011). The associated k and β parameters are presented in Table 3. In general, the k and β demonstrated ascending tendency ($p < 0.05$) with increasing PSC. Moreover, the DEY-stabilized dressings (except of control sample) at PSC ≥ 2 wt% and those prepared with SC at PSC ≥ 3 wt% yielded k values greater than unity, respectively. Whereas regarding β the higher than unity values were detected in dressings made with DEY at PSC ≥ 3 wt% and those prepared with SC at PSC ≥ 4 wt%. The found results may indicate that the structures of examined dressings with raising PSC were becoming more sensitive to shear forces than oscillatory movements, most probably due to the increasing inter- and intra-molecular associations or a gel-like structure (Manoi & Rizvi, 2009).

3.2. Physical stability and Bohlin's parameters

The determined physical stability parameters (PSPs) of salad dressings towards creaming (ESC) and fat holding capacity (FHC) are presented in Fig. 4a. The ESC and FHC were positively ($p < 0.01$) correlated with increasing PSC, however the differences between corresponding DEY- and SC-stabilized samples were in majority insignificant ($p < 0.05$). ANOVA revealed that PSC had a predominant ($p < 0.001$) effect on the increase of PSPs and the exponential functions were used to describe ESC evolution (Table 2). The values of ESC increased gradually up to 3 wt% PS and then steeply in samples containing ≥4 wt% PS. Whereas, regarding FHC slow progressive trend was observed up to 4 wt% PS. At the applied measurement conditions the values of FHC and ESC reached 100% in dressings containing 4 and 5 wt% PS, respectively. In general these results confirmed our previous findings (Bortnowska et al., 2014) and the explanation may be attributed to increasing water holding capacity and viscosity of the dressings. Consequently, in more viscous systems the droplets movement probably was slowed down and the particles were immobilized in the biopolymers gel network (Dickinson, 2003; Farshchi et al., 2013; Mun et al., 2009). The values of Bohlin's parameters (*A* and *z*) are presented in Fig. 4b. The *z* parameter is a measure of the number of rheological units correlated with one another in the three-dimensional structure, and the A one is related to the strength of the interactions between these units (Laca et al., 2010). ANOVA revealed that PSC had predominant effect ($p < 0.001$) on the increase of both examined Bohlin's parameters (BPs) and the functions used for their modeling are shown in Table 2. At PSC ≤ 2 wt% BPs changes were insignificant ($p < 0.05$), whereas further increase of PSC induced their rapid development in both studied systems. Moreover, it has been also found that at PSC ≥ 3 wt% corresponding DEY-stabilized dressings yielded in majority greater values of BPs than those prepared with SC and this partly is opposite to the effects detected in our previous study (Bortnowska et al., 2014). The *z* values were considerably ($p < 0.05$) correlated with those of ESC and FHC what may suggest that increasing PSC allowed to better keep original dressing microstructure as well as prevent creaming of the emulsion droplets (Manoi & Rizvi, 2009; Zaidel, Chronakis, & Meyer, 2013). Compared to full-fat mayonnaises, the tested dressings demonstrated lower *A* values even at the highest PSC, whereas the *z* ones at PSC ≥ 4 wt% were on the comparable level (Laca et al., 2010; Mancini et al., 2002).

3.3. Texture parameters

The determined texture parameters (TPs) of salad dressings are presented in Fig. 5a and b. Irrespectively of the applied ET, with raising PSC greater values of TPs were observed, however generally significant ($p < 0.05$) differences between consecutive samples were observed at PSC ≥ 3 wt%. ANOVA revealed that, the PSC exerted greater ($p < 0.001$) than ET influence on the increase of TPs and firmness fit well with quadratic functions in both examined sets of dressings (Table 2). Moreover, it was observed that increasing PSC yielded in majority higher values of TPs in DEY- than SC-stabilized dressings and particularly appreciable ($p < 0.05$) differences were found regarding consistency and adhesiveness at PSC ≥ 3 wt%. Consistency and adhesiveness are related parameters, consistency indicates the thickness of the dressing, while the adhesiveness gauges the resistance of the sample to flow off the disc during back extrusion and also is referred to the viscosity

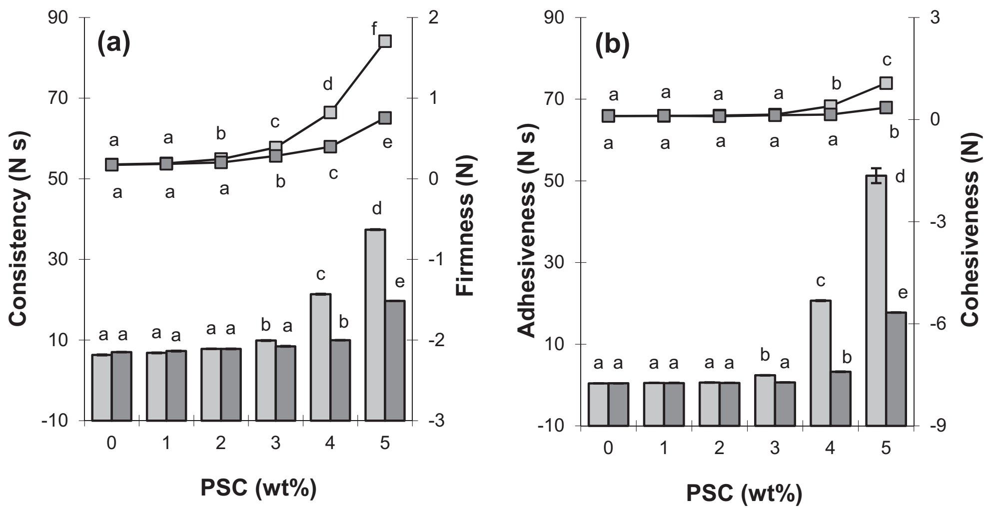

Fig. 5. Effects of potato starch concentration (PSC) on: consistency (columns) and firmness (a), adhesiveness (columns) and cohesiveness (b) of salad dressings prepared with dried egg yolk and sodium caseinate. Mean values (within the same parameters) marked with no common letters are significantly different ($p < 0.05$). (◊) DEY; (▬) SC; (▢) DEY; (■) SC.

(Ciron, Gee, Kelly, & Auty, 2010; Liu et al., 2007). In both studied systems, the consistency values were significantly ($p < 0.05$) correlated to those of K and z derived from H-B model and Bohlin's relation, respectively. Moreover, at PSC ≥ 3 wt%, the z values were in majority greater ($p < 0.05$) in DEY-than SC-stabilized dressings (Fig. 4b). Regarding adhesiveness (viscosity), the results are generally in good agreement with those achieved from steady-state flow measurements (Fig. 1a and b). Moreover in both explored systems, adhesiveness was significantly ($p < 0.01$) correlated to firmness, A and G_N^0. Hence, it would appear reasonable to postulate that except reasons discussed earlier (Section 3.1) also the extent of the three dimensional network formation and differentiated order of magnitude of interactions between molecules contributed to the found discrepancies of consistency and adhesiveness between DEY- and SC-stabilized dressings (Ciron, Gee, Kelly, & Auty, 2010; Zaidel et al., 2013).

3.4. Color changes

Color changes of salad dressings were determined with respect to: color distance ($\Delta E_{a^*b^*}$), whiteness index (WI), total color difference (ΔE) and hue angle (H°) (Table 4). Raising PSC increased values of $\Delta E_{a^*b^*}$ in both examined systems and as reflected by F values (ANOVA) this parameter was mostly ($p < 0.001$) affected by PSC. The quadratic functions were used for modeling $\Delta E_{a^*b^*}$ evolution (Table 2). Moreover, Pearson correlation test displayed that $\Delta E_{a^*b^*}$ was particularly well correlated to lightness (L^*) ($p < 0.001$). Changes of WI appeared to be rather small and oppositely to $\Delta E_{a^*b^*}$ more affected ($p < 0.001$) by ET than PSC. In addition, in dressings prepared with DEY and SC ascending and declining tendencies regarding this parameter were observed, respectively. In samples made with DEY the WI was relatively high correlated to L^* ($p < 0.01$), whereas in those prepared with SC to b^* ($p < 0.001$). The ΔE was studied to estimate magnitude of color differences between dressing samples. This parameter showed increasing trend with raising PSC, similarly as we found in our previous study (Bortnowska et al., 2014), however according to ANOVA ΔE was more influenced by ET ($p < 0.001$) than by PSC. Moreover, Pearson correlation test revealed that ΔE was considerably ($p < 0.01$) correlated with all studied color coordinates. The H° describing qualitative attribute of color was systematically depressed ($p < 0.001$) with enhancing PSC, and this shows slowly decrease of dressings yellowness. In addition, in both sets of samples H° was significantly ($p < 0.001$) correlated with a^* and b^*. The found relationship between lightness (L^*) and studied determinants of color changes ($\Delta E_{a^*b^*}$, WI, ΔE) may be related to the increasing light scattering with raising polymer concentration in the continuous phase of dressings (Chung, Degner, & McClements, 2013; Mun et al., 2009). Moreover, interfacial complexation between surface active components covering oil droplets and starch molecules may have induced increase in droplet diameter (Bortnowska et al., 2014) and due to the variations in light wave absorption affected all studied color coordinates (McClements, 2002).

3.5. Correlations among sensory features and instrumentally detected parameters

Parameters determined sensorially (by hand, H) and instrumentally (I) were compared and the correlation values are presented in Table 5. It was found that in majority the correlations were

Table 4
Changes in color of salad dressings.

	DEY-stabilized salad dressings						SC-stabilized salad dressings					
	PS (wt%)											
	0	1	2	3	4	5	0	1	2	3	4	5
$\Delta E_{a^*b^*}$	76.1a	77.5b	78.7b	80.3c	81.9d	84.8e	88.7f	89.6fg	90.4gh	90.8gh	91.7hi	92.1i
WI	69.7a	69.0a	69.5a	70.4b	71.3c	72.6d	80.3e	78.6f	78.5f	78.2fg	78.3fg	77.9g
ΔE^*	–	3.07a	4.11b	5.45c	6.81d	9.98e	–	1.66f	2.34fg	2.80g	3.71h	4.19h
H°	88.5a	84.1b	83.0b	82.1bc	81.8bc	79.5c	104d	96.3e	94.6ef	91.9f	88.7g	87.6g

For the definition of abbreviations, see Section 2. Within the rows, values followed by different letters are significantly different ($p < 0.05$).

Table 5
Pearson correlation coefficients among sensory (by hand, *H*) attributes and instrumental (*I*) features of salad dressings.

Emulsifier	FLY (H) – σ_0 (I)	FIS ($H-I$)	COY ($H-I$)	COS ($H-I$)	ADS ($H-I$)
DEY	0.919**	0.954**	0.904*	0.981***	0.889*
SC	0.882*	0.936**	0.807	0.954**	0.806

FLY, flowability. σ_0, yield stress. FIS, firmness. COY, consistency. COS, cohesiveness. ADS, adhesiveness. Significance level, $^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

significant, and higher in DEY- than SC-stabilized dressings. Satisfactory relationship between sensory and instrumental measurements was detected in our previous work (Bortnowska et al., 2013) and by Pereira et al. (2003). On the other hand, the revealed disparity between sensory and instrumental assessments reflected by insignificant correlation values may be related to the differences in measurement geometry that was used in TPA test, and manual evaluations. Taking into account that tactile sensory attributes of dressings could be related to their rheological properties (Laca et al., 2010), the scores obtained for consistency detected by sensory perception in the mouth were compared with the values of K, determined instrumentally using shear rates 1–50 s^{-1}, i.e. in the range which food may experience in the mouth during mastification (Bortnowska et al., 2013). Experimental and sensory results were subjected to the modified Stevens equation, obtaining following coefficients: $S_0 = 4.019$, $\alpha = 0.2722$ ($R^2 = 0.9945$) and $S_0 = 3.799$, $\alpha = 0.2962$ ($R^2 = 0.9704$) in DEY- and SC-stabilized dressings, respectively. Similar values of α found Laca et al. (2010) in mayonnaises prepared with EY granules, however the S_0 values detected in the current study were much smaller, assumably due to the lower oil content.

4. Conclusions

The studies showed that pregelatinized PS addition caused marked changes of physicochemical properties and stability of low-fat salad dressings prepared with DEY or SC. The flow characteristics were non-Newtonian with shear-thinning behavior that was well described by Herschel–Bulkley model whose K and σ_0 parameters were modeled by exponential functions. As oscillatory test revealed, dressings containing ≤2 wt% PS demonstrated liquid character ($\tan\delta > 1$), whereas those supplemented with ≥3 wt% PS showed gel-like structure ($\tan\delta < 1$). Increasing PS concentration yielded greater values of texture parameters, more in DEY- than SC-stabilized dressings, which were well correlated with non-oral sensory attributes. The accelerated ageing test revealed that PS addition of 5 wt% was sufficient to stabilize dressings towards creaming and fat holding capacity. The presented results could be very useful to the food industry by manufacturing low-fat salad dressings containing heat-sensitive natural ingredients because their supply have increased considerably in recent years due to the high acceptance of the consumers.

References

Ahmadi-Abhari, S., Woortman, A. J. J., Hamer, R. J., Oudhuis, A. A. C. M., & Loos, K. (2013). Influence of lysophosphatidylcholine on the gelation of diluted wheat starch suspensions. *Carbohydrate Polymers*, *93*, 224–231.

Bortnowska, G., Balejko, J., Tokarczyk, G., Romanowska-Osuch, A., & Krzemińska, N. (2014). Effects of pregelatinized waxy maize starch on the physicochemical properties and stability of model low-fat oil-in-water food emulsions. *Food Hydrocolloids*, *36*, 229–237.

Bortnowska, G., Krzemińska, N., & Mojka, K. (2013). Effects of waxy maize and potato starches on the stability and physicochemical properties of model sauces prepared with fresh beef meat. *International Journal of Food Science and Technology*, *48*, 2668–2675.

Chang, F., He, X., & Huang, Q. (2013). The physicochemical properties of swelled maize starch granules complexed with lauric acid. *Food Hydrocolloids*, *32*, 365–372.

Chung, C., Degner, B., & McClements, D. J. (2013). Designing reduced-fat food emulsions: Locust bean gum–fat droplet interactions. *Food Hydrocolloids*, *32*, 263–270.

Ciron, C. I. E., Gee, V. L., Kelly, A. L., & Auty, M. A. E. (2010). Comparison of the effects of high-pressure microfluidization and conventional homogenization of milk on particle size, water retention and texture of non-fat and low-fat yoghurts. *International Dairy Journal*, *20*, 314–320.

Copeland, L., Blazek, J., Salman, H., & Tang, M. C. (2009). Form and functionality of starch. *Food Hydrocolloids*, *23*, 1527–1534.

Dickinson, E. (2003). Hydrocolloids at interfaces and the influence on the properties of dispersed systems. *Food Hydrocolloids*, *17*, 25–39.

Diftis, N. G., Biliaderis, C. G., & Kiosseoglou, V. D. (2005). Rheological properties and stability of model salad dressing emulsions prepared with a dry-heated soybean protein isolate-dextran mixture. *Food Hydrocolloids*, *19*, 1025–1031.

Dolz, M., Hernández, M. J., & Delegido, J. (2006). Oscillatory measurements for salad dressings stabilized with modified starch, xanthan gum, and locust bean gum. *Journal of Applied Polymer Science*, *102*, 897–903.

Drakos, A., & Kiosseoglou, V. (2008). Depletion flocculation effects in egg-based model salad dressing emulsions. *Food Hydrocolloids*, *22*, 218–224.

Farshchi, A., Ettelaie, R., & Holmes, M. (2013). Influence of pH value and locust bean gum concentration on the stability of sodium caseinate-stabilized emulsions. *Food Hydrocolloids*, *32*, 402–411.

Gamonpilas, C., Pongjaruvat, W., Fuongfuchat, A., Methacanon, P., Seetapan, N., & Thamjedsada, N. (2011). Physicochemical and rheological characteristics of commercial chili sauces as thickened by modified starch or modified starch/xanthan mixture. *Journal of Food Engineering*, *105*, 233–240.

Huck-Iriart, C., Álvarez-Cerimedo, M. S., Candal, R. J., & Herrera, M. L. (2011). Structures and stability of lipid emulsions formulated with sodium caseinate. *Current Opinion in Colloid & Interface Science*, *16*, 412–420.

Kaur, B., Ariffin, F., Bhat, R., & Karim, A. A. (2012). Progress in starch modification in the last decade. *Food Hydrocolloids*, *26*, 398–404.

Khwaldia, K., Banon, S., Perez, C., & Desobry, S. (2004). Properties of sodium caseinate film-forming dispersions and films. *Journal of Dairy Science*, *87*, 2011–2016.

Laca, A., Sáenz, M. C., Paredes, B., & Díaz, M. (2010). Rheological properties, stability and sensory evaluation of low-cholesterol mayonnaises prepared using egg yolk granules as emulsifying agent. *Journal of Food Engineering*, *97*, 243–252.

Liu, H., Xu, X. M., & Guo, Sh. D. (2007). Rheological, texture and sensory properties of low-fat mayonnaise with different fat mimetics. *Lebensmittel-Wissenschaft Und-Technologie*, *40*, 946–954.

Lorenzo, G., Checmarev, G., Zaritzky, N., & Califano, A. (2011). Linear viscoelastic assessment of cold gel-like emulsions stabilized with bovine gelatin. *LWT-Food Science and Technology*, *44*, 457–464.

López, C. A., de Vries, A. H., & Marrink, S. J. (2012). Amylose folding under the influence of lipids. *Carbohydrate Research*, *364*, 1–7.

Ma, Z., Boye, J. I., Fortin, J., Simpson, B. K., & Prasher, S. O. (2013). Rheological, physical stability, microstructural and sensory properties of salad dressings supplemented with raw and thermally treated lentil flours. *Journal of Food Engineering*, *116*, 862–872.

Mancini, F., Montanari, L., Peressini, D., & Fantozzi, P. (2002). Influence of alginate concentration and molecular weight on functional properties of mayonnaise. *Lebensmittel-Wissenschaft Und-Technologie*, *35*, 517–525.

Manoi, K., & Rizvi, S. S. H. (2009). Emulsification mechanisms and characterizations of cold, gel-like emulsions produced from texturized whey protein concentrate. *Food Hydrocolloids*, *23*, 1837–1847.

McClements, D. J. (2002). Colloidal basis of emulsion color. *Current Opinion in Colloid and Interface Science*, *7*, 451–455.

Moros, J. E., Franco, J. M., & Gallegos, C. (2002). Rheology of spray-dried egg yolk-stabilized emulsions. *International Journal of Food Science and Technology*, *37*, 297–307.

Mun, S., Kim, Y.-L., Kang, C.-G., Park, K.-H., Shim, J.-Y., & Kim, Y.-R. (2009). Development of reduced-fat mayonnaise using 4αGTase-modified rice starch and xanthan gum. *International Journal of Biological Macromolecules*, *44*, 400–407.

Pereira, R. B., Singh, H., Munro, P. A., & Luckman, M. S. (2003). Sensory and instrumental textural characteristics of acid milk gels. *International Dairy Journal*, *13*, 655–667.

Putseys, J. A., Lamberts, L., & Delcour, J. A. (2010). Amylose-inclusion complexes: Formation, identity and physico-chemical properties. *Journal of Cereal Science*, *51*, 238–247.

Shah, A., Zhang, G., Hamaker, B. R., & Campanella, O. H. (2011). Rheological properties of a soluble self-assembled complex from starch, protein and free fatty acids. *Journal of Food Engineering*, *105*, 444–452.

Singh, N., Singh, J., Kaur, L., Sodhi, N. S., & Gill, B. S. (2003). Morphological, thermal and rheological properties of starches from different botanical sources. *Food Chemistry*, *81*, 219–231.

Udomrati, S., Ikeda, S., & Gohtani, S. (2013). Rheological properties and stability of oil-in-water emulsions containing tapioca maltodextrin in the aqueous phase. *Journal of Food Engineering*, *116*, 170–175.

Utrilla-Coello, R. G., Rodríguez-Huezo, M. E., Carrillo-Navas, H., Hernández-Jaimes, C., Vernon-Carter, E. J., & Alvarez-Ramirez, J. (2014). In vitro digestibility, physicochemical, thermal and rheological properties of banana starches. *Carbohydrate Polymers*, *101*, 154–162.

Xie, F., Yu, L., Su, B., Liu, P., Wang, J., Liu, H., et al. (2009). Rheological properties of starches with different amylose/amylopectin ratios. *Journal of Cereal Science*, *49*, 371–377.

Zaidel, D. N. A., Chronakis, I. S., & Meyer, A. S. (2013). Stabilization of oil-in-water emulsions by enzyme catalyzed oxidative gelation of sugar beet pectin. *Food Hydrocolloids*, *30*, 19–25.