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Dielectric properties and other physical properties of low-acyl gellan gel as relevant to microwave assisted pasteurization process

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ABSTRACT

Various model foods were needed as chemical marker carriers for the heating pattern determination in developing microwave heating processes. It is essential that these model foods have matching physical properties with the food products that will be microwave processed, such as meat, vegetables, pasta, etc. In this study, the physical properties of low acyl gellan gel were investigated to evaluate its suitability to be used as a possible model food for the development of single mode 915 MHz microwave assisted pasteurization processes. These physical properties included the dielectric properties, gel strength and water holding capacities. In order to adjust the dielectric constant and loss factor, various amounts of sucrose (0, 0.1, 0.3 and 0.5 g/mL (solution)) and salt (0, 100, 200, and 300 mM) were added to 1% gellan gel (with 6 mM Ca^{2+} addition). Results showed that sucrose and salt addition were effective for the adjustment of the dielectric constants and loss factor of gellan gels, respectively. Regression equations were developed to predict the relationship between the dielectric properties of gellan gel with sucrose content, salt content, and temperature (22–100 °C) at 915 MHz, and thus can be used to determine the formulation of a gellan gel model food to match the dielectric properties of a certain food that will be processed. The gellan gels with sucrose content of 0, 0.1 and 0.3 g/mL (solution) showed relatively high gel strength for post microwave process handling. However, the addition of 0.5 g/mL (solution) sucrose significantly decreased the gel strength, resulting in highly deformable gels. The water holding capacities of all the gels increased with increasing sucrose content, while the effect of salt was not consistent.

1. Introduction

915 MHz single mode microwave assisted thermal processing systems have been developed at Washington State University (Pullman, WA) to produce both shelf stable and refrigerated food products with better quality and nutrition attributes compared with the traditionally thermal processed foods (Zhang et al., 2013). Similar to conventional thermal processing such as canning, it is critical to monitor the temperature profile at cold spots inside food packages to develop a reliable process which ensures adequate thermal sterility. Due to the difficulty of heating pattern determination for microwave processes, different model food and chemical marker systems were developed to model the real foods and predict the cold spot and hot spot locations (Pandit et al., 2006, 2007). Whey protein gels (WPG) are used as model foods for microwave assisted thermal sterilization (MATS) processes (Lau et al., 2003; Wang et al., 2009). However, due to the relatively high gelation temperatures of the model foods used for MATS processes, new model food systems including egg white and whole egg gel models were developed for microwave assisted pasteurization (MAP) processes at temperatures higher than 70 and 80 °C, respectively (Zhang et al., 2013, 2014).

In order to develop a model food system that can be used for processes at temperatures lower than 70 °C, other food gel systems which can be formed at pasteurization temperatures were considered. Gellan gum is an extracellular polysaccharide secreted by the bacterium *Sphingomonas elodea* (formerly known as *Pseudomonas elodea*) (Pollock, 1993). It is a linear anionic monosaccharide with a repeating unit of β-D-glucose, β-D-glucuronic acid, and α-L-rhamnose (molar ration 2:1:1) (Kuo and Mort, 1986). Low acyl gellan gum is a deacyled form of the native gellan gel. It is formed when both acyl groups of the native gellan gum are hydrolyzed when exposed to alkali and high temperatures. Unlike the high acly gellan gum, low acyl gellan gum forms strong, clear and brittle gels with addition of proper concentrations of cations (Mao et al., 2000). It has the advantages of relatively low gelation temperature (Morris et al., 2012) and high gelling efficiency to produce a wide

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range of mechanical properties (Sworn, 2009). Therefore, the physical properties of low acyl gellan gel were studied.

Dielectric properties is one of the important criteria for selecting proper model foods for microwave heating since it determines how the microwave energy is absorbed, transmitted, reflected, or concentrated inside a food material (Datta and Anantheswaran, 2001). The relative permittivity is defined as $\varepsilon_r = \varepsilon/\varepsilon_0$, which is the ratio of the amount of electrical energy stored in a material by an applied voltage (ε), relative to that stored in vacuum or free space (ε_0, 8.8542×10^{-12} F/m). It consists of two parts expressed as:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{1}$$

where $j = \sqrt{-1}$; ε_r' is dielectric constant, which indicates the ability of a material to store electric energy; ε_r'' is the dielectric loss factor, which reflects the ability of a material to convert electromagnetic energy into heat. The rate of energy generation per unit volume (Q) in a food can be calculated from:

$$Q = \rho C_P \frac{\Delta T}{\Delta t} = 2\pi f \varepsilon_0 \varepsilon_r'' E^2 \tag{2}$$

where ρ is the density of the material (kg/m^3), C_p is the specific heat of the material (J/kg °C), ΔT is the temperature increase (°C), t is the time (s), f is the frequency (Hz), and E is the strength of electric field of the wave (V/m). The only published study that has been done on the dielectric properties of gellan gel was reported by Okiror and Jones (2012) on the effect of temperature on the dielectric properties of 1% gellan gel containing 0.17% and 0.3% $CaCl_2$. However, in order to use gellan gel as a model food with a wide range of dielectric properties, it is necessary to have more comprehensive information on how its dielectric properties can be adjusted. Since the dielectric constant is mainly affected by the free water inside a food material (Sun et al., 1995), sucrose was considered to be added to the gellan gel network to decrease the free water contents, so that the dielectric constant values could be adjusted. Moreover, it was reported that adding sucrose could increase the gellan gel clarity and strength at proper cation concentration levels (Tang et al., 2001). Therefore, the effect of sucrose addition of 0–0.5 g/ (mL solution) was investigated in this study. Salt addition has been widely reported to increase the dielectric loss factor of food materials (Guan et al., 2004; Wang et al., 2009; Zhang et al., 2013). Therefore, the effect of 0–300 mM salt addition to gellan gel was also evaluated.

Since the chemical markers (which serve as color agents for heating pattern analysis) need to be added before the gelation of model food gels, gelation temperature is another important factor for the evaluation of a possible model food. Due to the relatively low processing temperature of 70–100 °C during MAP processes, it is important that the gelation temperature of the possible model foods to be lower than 70 °C. Tang et al. (1997a) studied the gelation temperatures of gellan solutions covering a relatively large cation (Ca^{2+}, 2–40 mM) and gellan gum (0.4–2%, w/v) concentration range. The results showed that gellan gel gelation temperatures varied from 30 to 72 °C depending on the polymer and cation concentrations. They also developed a mathematical model to predict the gelation temperature of gellan gel with consideration of gellan gum, monovalent and divalent cation concentrations as:

$$\begin{aligned}\frac{1}{T_{gel}} &= 3.33 \times 10^{-3} - 1.34 \times 10^{-4}[X_P] \\ &\quad - 2.33 \times 10^{-4}\log_{10}[0.0726X_{Na} + 0.111X_K + X_{Ca} + X_{Mg}]\end{aligned} \tag{3}$$

where T_{gel} is the gelation temperature in K, X_p, X_{Na}, X_K, X_{Ca}, and X_{Mg} are concentrations of gellen gum (%), and concentrations (mM) of added Na^+, K^+, Ca^{2+}, and Mg^{2+} (Tang et al., 1997b). With the addition of 6 mM Ca^{2+} and 0, 100, 200, and 300 mM Na^+, the gelation temperatures of the 1% gellan gel used in this study were calculated according to Eq. (3) as 44.4, 52.7, 57.5, and 60.9 °C, respectively. Tang et al. (2001) also reported that the addition of sucrose (0–35%, w/v) increased the gelation temperature of gellan gel by 1.5–3 °C, which indicated the gelation temperature of gellan gel used in this study be highly possible below 70 °C.

Gel strength and water holding capacities are two other important criteria for model foods evaluation (Zhang et al., 2013). The gel strength determines whether the gel is strong enough for post microwave process handling, while water holding capacity indicates the stability of a gel to hold its original shape during process and storage. The effects of gellan gum, cations, and sugar contents on the gellan gel texture and water holding capacities have been widely studied (Moritaka et al., 1991; Tang et al., 1994, 1995, 1996). However, the effect of the combination of cations and sucrose addition on the gel strength and water holding capacity of gellan gel was not covered and will be investigated in this study.

2. Materials and methods

2.1. Sample preparation

Low acyl gellan gum samples (KELCOGEL F) was provided by CP Kelco Inc. (Atlanta, GA). Gellan gum powder was slowly added to distilled water at room temperature to obtain a final dispersion of 1% (w/v) polymer concentration. The mixture was further mixed on a magnetic stir for 1 h, and left at room temperature overnight for better rehydration. The mixture was then gently heated to 90 °C and became a clear solution. $CaCl_2{\cdot}2H_2O$ (J.T. Baker, Avantor Performance Materials, Inc., Phillipsburg, NJ) was added to the hot solution at 90 °C to obtain a Ca^{2+} concentration of 6 mM, to ensure the formation of a strong gellan gel network. Besides Ca^{2+}, NaCl and/or sucrose were also added to the hot solution following the experimental design shown in Table 1 to obtain Na^+ concentrations of 0, 100, 200, and 300 mM and/or sucrose concentrations of 0, 0.1, 0.3 and 0.5 g/mL (solution). These solutions were further heated and stirred at 90 °C for 30 s, and allowed to cool at room temperature to around 75 °C and filled into 50 mL plastic centrifuge tubes. The tubes were left at room temperature overnight to form consistent gels. The gel samples of batch I and II were later used for dielectric property measurements while sample batch III were used for the determination of gel strength and water holding capacity. For each physical property measurement, triplicate sets of samples were prepared.

2.2. Dielectric properties measurement

Dielectric properties of gellan gel samples were measured using an HP 8752 C Network Analyzer (frequency range: 0.3–3 GHz) and 85070B Open-End Coaxial Dielectric Probe (Agilent Technologies, Santa Clara, CA). A stainless steel tube with sharp edges was used to cut the samples into cylindrical specimens (diameter = 21 mm) to fit in the test cell. The measurements were carried out following the procedures reported before (Zhang et al., 2013) at temperatures of 22, 30, 40, 50, 60, 70, 80, 90, and 100 °C. All measurements were conducted in triplicate.

Table 1
Components of the gellan gel samples with different cation and sucrose contents.

Sample batch	Ca^{2+} (mM)	Na^+ (mM)	Sucrose (g/mL, solution)
I	6	0, 100, 200, and 300	0
II	6	0	0, 0.1, 0.3, and 0.5
III	6	0, 100, 200, and 300	0, 0.1, 0.3, and 0.5

2.3. Penetration depth

Penetration depth (D_p) of microwave power is the depth where the incident power decreases to $1/e$ ($e = 2.718$) of its original value at the material surface. It indicates the heating uniformity and is an important parameter for microwave process development. D_p can be calculated as:

$$D_P = \frac{c}{2\pi f\sqrt{2\varepsilon_r'\left[\sqrt{\left(\frac{\varepsilon''}{\varepsilon'}\right)^2+1}-1\right]}} \tag{4}$$

where c is the speed of light in free space (3×10^8 m/s), and f is the frequency (Hz) (Buffler, 1993), which is 915 MHz in this study.

2.4. Gel strength measurement

Gel samples in batch III were used for gel strength measurements. A TA-XT2i Texture Analyzer (Texture Technologies Corp, Scarsdale, NY) equipped with a 25 kg load cell and 40 mm plate probe was used to conduct the uniaxial compression tests for gel strength determination. A stainless steel tube with sharp edges was used to cut the gel samples into cylindrical specimens (diameter = 21 mm, height = 20 mm). The specimens were placed under the plate probe and deformed at a constant cross head speed of 1 mm/s till 70% deformation. The probe then returned to with the original position a speed of 2 mm/s. The maximum force (F_{max}) and deformation (ΔL_{max}) at failure for each gel specimen were obtained. The compression tests were repeated with six different samples. The true gel stress (σ_{max}) and gel strain (ε_{max}) at failure for cylindrical specimens during compression tests were calculated according to Hamann (1983) as:

$$\varepsilon_{max} = -\ln\left[1 - \frac{\Delta L_{max}}{L}\right] \tag{5}$$

$$\sigma_{max} = \frac{F_{max}(L - \Delta L_{max})}{\pi R^2 L} \tag{6}$$

where L is the original length of the gel specimen and R is the original radius. For cylindrical samples, the failure during compression tests was observed to take place in the mode of shear. Therefore, the shear stress (τ_{max}) and shear strain ($\gamma_{\max}$) at failure can be calculated from:

$$\gamma_{max} = (1 + v)\varepsilon_{max} \tag{7}$$

$$\tau_{max} = \frac{\sigma_{max}}{2} \tag{8}$$

where v is the Possion's ratio (assumed as 0.5 for impressible gel sample). γ_{max} represents the extensibility of gel at the point of failure, while τ_{max} reflects the strength of the gel (Tang et al., 1995).

2.5. Measurement of water holding capacity (WHC)

Small cylindrical specimens (diameter = 5 mm, length = 10 mm) were taken from the gels in sample batch III using a plastic tube. The weight of the specimen was recorded as w_0. The sample was then placed in Costar Spin-X Centrifuge Tube Filters (Cole-Parmer, Vernon Hills, IL) with pores of 0.45 μm and centrifuged at 2000 rpm (268 g) for 5 min (Mao et al., 2001). The weight of the specimen right after the centrifuge was then recorded as w. Four replicates were conducted for each measurement. The water holding capacity was calculated as:

$$WHC = \frac{w}{w_0} \tag{9}$$

2.6. Statistical analysis

The results for each physical property obtained from replicated measurements were processed using Microsoft Excel (Microsoft Corporation, Redmond, WA) and were shown as Means ± Standard deviation. The version 14.1 Minitab software (Minitab Inc., State College, PA) was used to obtain the correlation coefficients and ANOVA tests with a significance level of $p = 0.05$.

3. Results and discussion

3.1. Combined effect of frequency and temperature on dielectric properties

The dielectric constant and loss factor of 1% gellan gel with 6 mM Ca^{2+} addition at frequencies between 0.3 and 3 GHz and temperatures between 22 and 100 °C are shown in Fig. 1. The dielectric constant value of the gel sample was similar to those reported by Okiror and Jones (2012), while the dielectric loss factor values were smaller because of the lower Ca^{2+} concentration in our study (0.17% and 0.3% in their study). The dielectric constant of gellan gels decreased slightly with frequency and temperature, while the changes of loss factor were more complicated. The dielectric loss factor is mainly contributed by two parts, namely, the dipole loss (ε_{rd}'') and ionic loss ($\varepsilon_{r\sigma}''$). Ionic loss is caused by the moving charged particles in an alternating electric field due to dissolved electrolytes. It typically predominates at frequencies lower than 1 GHz (Wang et al., 2011). The ionic loss factor of a material is related to its ionic conductivity (σ) in the relationship as (Hasted, 1973):

$$\varepsilon_{r\sigma}'' = \frac{\sigma}{2\pi f \varepsilon_0} \tag{10}$$

By taking a logarithm of both side of Eq. (10), one obtains:

$$log\varepsilon_{r\sigma}'' = -logf + log\frac{\sigma}{2\pi\varepsilon_0} \tag{11}$$

where for a certain material with a certain ionic conductivity (σ), the last item in Eq. (11) $log\frac{\sigma}{2\pi\varepsilon_0}$ is constant.

This can be used to explain the linear decrease of loss factor with increasing frequency at lower than 0.9 GHz shown in Fig. 1b. The loss factor started to increase at a certain frequency value between 0.9 and 2.7 GHz depending on different temperature, which indicated the increasing effect of dipole loss caused by the dipole polarization of water molecules. Similar phenomena were found in many other researches for materials such as mashed potato (Guan et al., 2004), gellan gel (Okiror and Jones, 2012), and egg white (Zhang et al., 2013). At frequencies higher than 2.7 GHz, the loss factor increased with increasing frequency while decreased with temperature, showing the predominant role of dipole loss.

3.2. Effect of sucrose content on the dielectric properties

The overall effects of temperature and frequency on dielectric properties of gellan gel with 0.3 g/mL (solution) sucrose content are shown in Fig. 2. Adding sucrose to the gellan formulation significant reduced the dielectric constant (Fig. 2a). The declining of dielectric constant with frequency was more significant at lower temperatures and higher frequencies. Sucrose addition also changed the overall effect of temperature and frequency on the dielectric loss factor (Fig. 2b). The frequencies at which the loss factor changed from decreasing to increasing with frequency moved to lower frequency range of 0.6 to 1.5 GHz depending on gel temperature. This phenomenon could be attributed to the change of relaxation time according to the Debye Equation (Debye, 1929) which

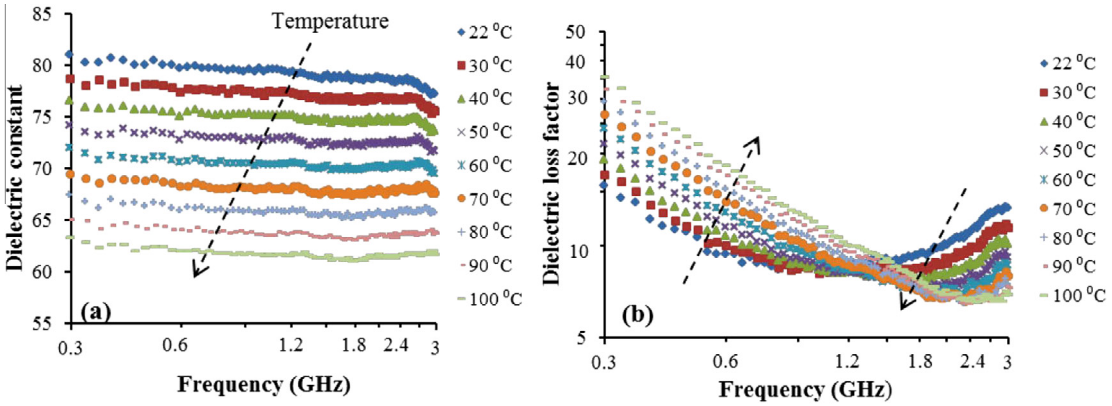

Fig. 1. Effect of frequency and temperature on the dielectric constant (a) and loss factor (b) of 1% gellan gel with 6 mM Ca^{2+} addition.

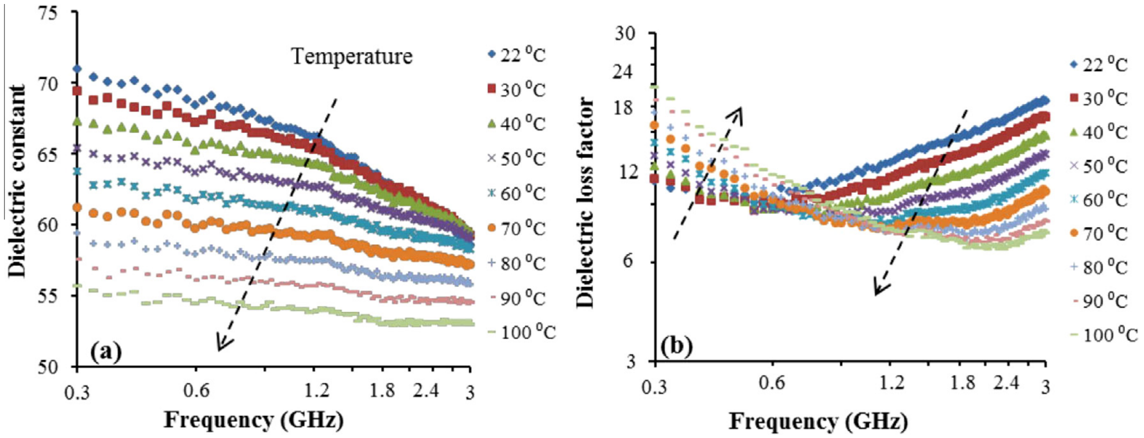

Fig. 2. Effect of frequency and temperature on the dielectric constant (a) and loss factor (b) of 1% gellan gel with 6 mM Ca^{2+} and 30% sucrose addition.

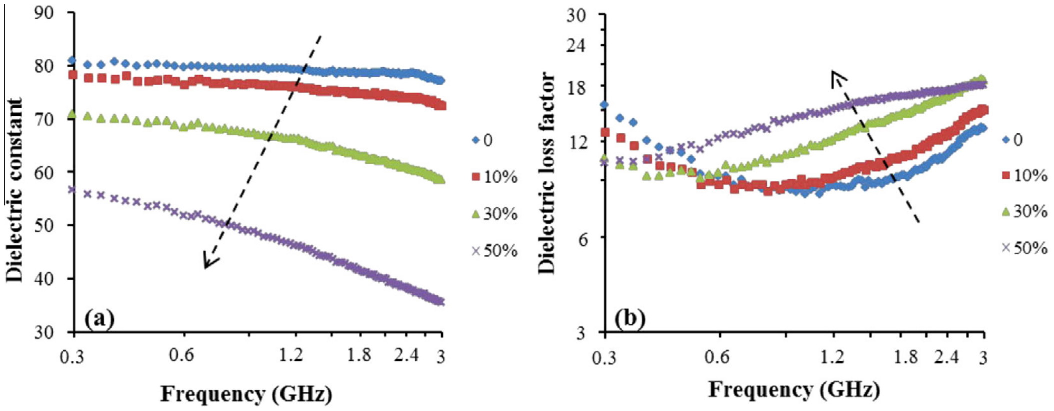

Fig. 3. Effect of sucrose content on the dielectric constant (a) and loss factor (b) of gellan gel at 22 °C between 0.3 and 3 GHz.

illustrated the frequency dependence of the dipolar loss mechanism. Adding sucrose reduced the free water content of the gellan gel and increased the amount of water bound to sucrose molecules which had much longer relaxation times, and therefore, lower relaxation frequencies (Tang, 2005).

The effect of sucrose content on the dielectric properties of gellan gel at 22 °C throughout the frequency range of 0.3–3 GHz is shown in Fig. 3. The dielectric constants of gellan gel without sucrose were similar to that of distilled water, which was also found by Okiror and Jones (2012) for gellan gel with 0.17% or 0.3% Ca^{2+}. Morris et al. (2012) stated that most water in biopolymer networks was free water, and therefore these biopolymers would show similar dielectric properties as free water. The dielectric constants decreased with increasing sucrose content at all frequencies, and the slopes of samples with higher sucrose contents were more inclined (Fig. 3a). It is likely that adding sucrose reduced the mobility of water due to the sugar-water association (Morris et al., 2012). The loss factor of gellan gel with no sucrose first decreased and then increased with increasing frequency. With the increase of sucrose content, the point where the loss factor started to increase moved to lower frequencies, which could be attributed to the decrease of relaxation frequency due to the increase of sucrose content.

At 915 MHz (0.915 GHz, the operation frequency of the MAP system), the changes in dielectric constant and loss factor of samples with sucrose over the tested temperature range of 22–100 °C are shown in Fig. 4. Similar as at the other frequencies, the dielectric constant significantly decreased with sucrose content. The dielectric constants at room temperature were reduced from 79.6 for samples without sucrose to 76.4, 67.4, and 48.9 for samples with 0.1, 0.3, and 0.5 g/mL (solution) sucrose contents, respectively. The effect of sucrose content on dielectric loss factor depended on temperature. At temperatures lower than 50 °C, the loss factor increased with increasing sucrose content. However, an opposite trend was found at temperatures higher than 60 °C. Similar results were found for gellan gels at 2450 MHz (data not shown). The regression equations relating the dielectric constant and loss factor with temperature and sucrose contents of the gellan gel were developed as:

$$Dielectric\ property = a + bT + cS + dT \times S + eT^2 + fS^2 \qquad (12)$$

where a, b, c, d, e, and f are regression coefficients, T is temperature (22–100 °C), and S is sucrose content (0–0.5 g/mL (solution)). The regression constants results and the coefficients of determination R^2 values at 915 and 2450 MHz are summarized in Tables 2 and 3, respectively.

3.3. Effect of salt content on the dielectric properties

Fig. 5 shows the combined effect of frequency and temperature on the dielectric properties of gellan gel with 200 mM salt. The dielectric constant of the gellan gel followed similar trend as that of the ones without salt addition as shown in Fig. 1a. Much higher loss factor values were found as comparing with the gellan gel with no salt addition. Due to the predominant role of ionic loss for gellan gel with the high ion concentrations, the loss factor decreased almost linearly throughout the tested frequency range (Tang, 2005). Deviation from the linear log–log curve was noticed at frequencies higher than 2.4 GHz at lower temperatures where the dipole loss started to show its importance.

The effect of salt addition of up to 300 mM on the dielectric properties of gellan gel is shown in Fig. 6. Adding salt reduced the dielectric constant, but significant differences were not found among samples with different salt contents. Mudgett (1986) attributed the effect of salt on dielectric constants to the reduced polarization of water by dissolved ions. Muley and Bolder (2013) further explained that the dissolved ions generated a solvation shell which trapped the free polar solvent around them, and thus reduced the polarization potential of the solvent. The dielectric loss factor value increased significantly with increasing salt content. The loss factor of gellan gel with no salt addition did not change linearly with frequency. For samples with 100–300 mM salt addition, the loss factor-frequency curves were linear at frequencies lower than 2.1 GHz, due to the major effect of ionic loss by high salt concentration.

Fig. 7 shows the effect of salt addition on the dielectric properties of gellan gel at 915 MHz at 22–100 °C. The dielectric constants decreased with temperature and showed no significant difference among samples with different salt contents ($p > 0.05$). But adding salt significantly increased the dielectric loss factor of the gellan gel samples. For example, the loss factor value at room temperature increased from 8.4 for sample without salt to 27.3, 47.1, and 62.8 for samples with 100, 200, and 300 mM salt contents, respectively. The difference was even larger at higher temperatures. At 100 °C, the loss factor values increased from 12.7 for gellan gel with no salt to 60.5, 108.2, and 150.4 for samples with 100, 200, and 300 mM salt addition, respectively. Similar results were found for samples at 2450 MHz (data not shown). Regression equations were also obtained to predict the relationship between dielectric properties, salt content, and temperature as shown in Eq. (12), where a, b, c, d, e, and f are regression coefficients, S represents salt (0–300 mM) instead of sucrose content. The regression results at

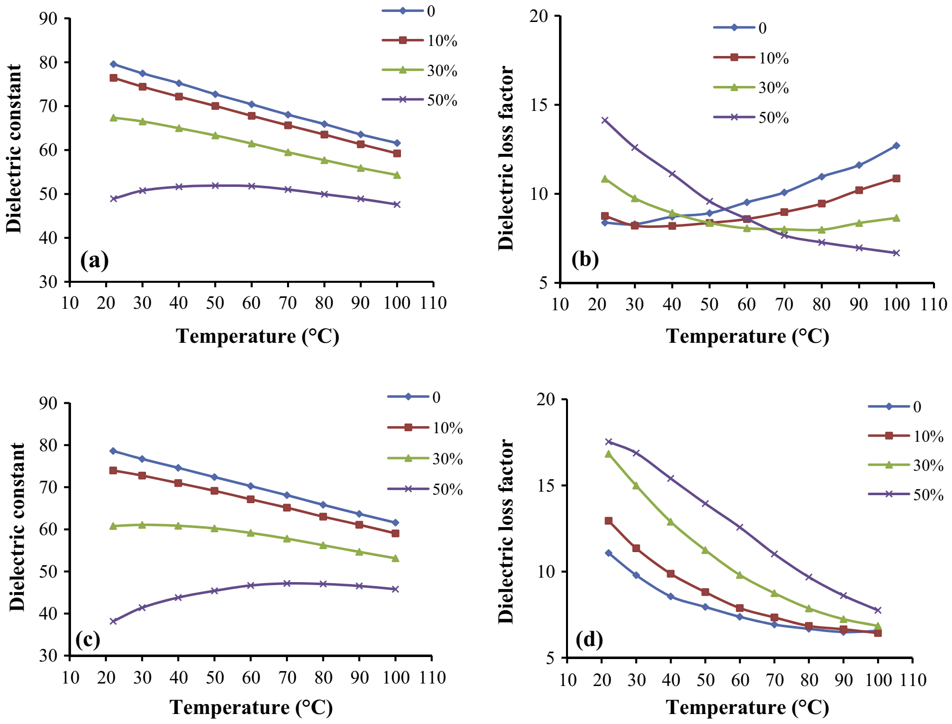

Fig. 4. Effect of sucrose content on the dielectric constant and loss factor of gellan gel at 915 (a and b) and 2450 (c and d) MHz between 22 and 100 °C.

Table 2
Regression constants and coefficients of determination in Eq. (12) for dielectric constant and loss factor of gellan gel with sucrose or salt addition at 915 MHz.

		a	b	c	d	e	f	R^2
Sucrose	ε_r'	85.56	−0.2528	−0.4164	0.0040	0	−0.0045	0.988
	ε_r''	9.186	−0.0564	0.0979	−0.0030	0.0010	0.0015	0.984
Salt	ε_r'	84.78	−0.2559	−0.0225	0.0001	0.0002	4.11E−05	0.997
	ε_r''	10.44	−0.1185	0.1300	0.0036	0.0015	−9.8E−05	0.999

Table 3
Regression constants and coefficients of determination in Eq. (13) for dielectric constant and loss factor of gellan gel with sucrose or salt addition at 2450 MHz.

		a	b	c	d	e	f	R^2
Sucrose	ε_r'	81.26	−0.1022	−0.6095	0.0061	−0.0012	−0.0053	0.991
	ε_r''	14.56	−0.1788	0.1850	−0.0016	0.0010	0.0001	0.985
Salt	ε_r'	83.07	−0.2177	−0.0267	7.65E−05	1.59E−05	4.65E−05	0.995
	ε_r''	15.04	−0.2164	0.04725	0.0014	0.0014	−4E−05	0.999

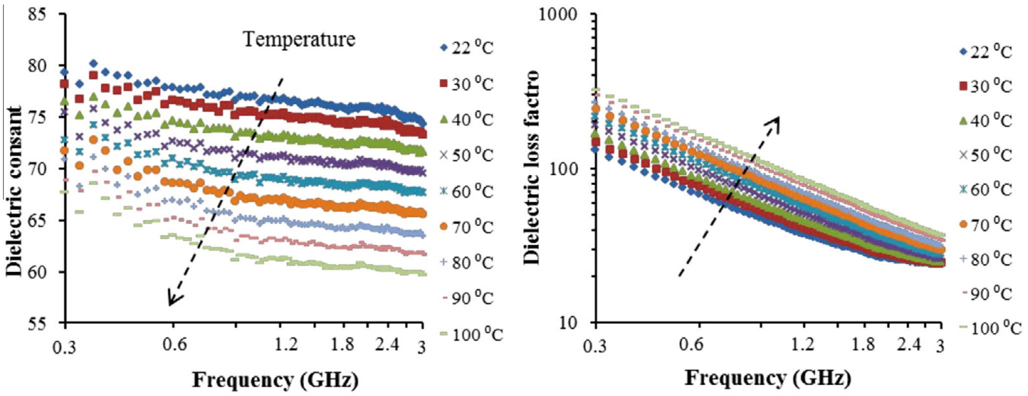

Fig. 5. Effect of frequency and temperature on the dielectric constant (a) and loss factor (b) of 1% gellan gel with 6 mM Ca^{2+} and 200 mM salt addition.

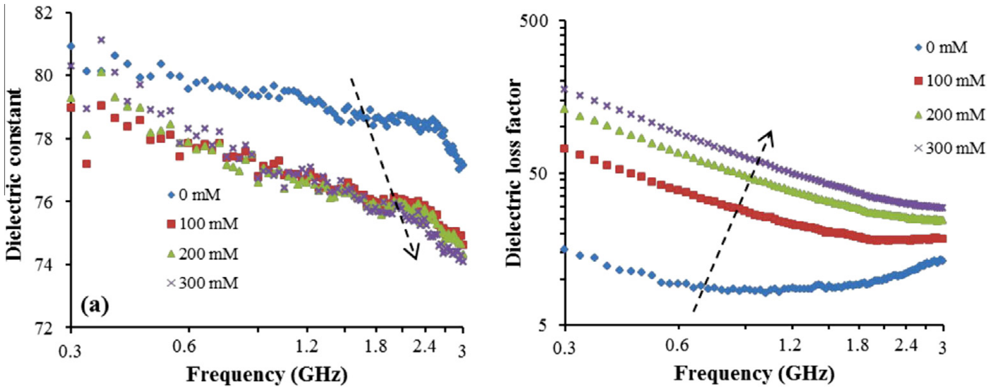

Fig. 6. Effect of salt content on the dielectric constant (a) and loss factor (b) of gellan gel at 22 °C between 0.3 and 3 GHz.

915 and 2450 MHz were also summarized in Tables 2 and 3, respectively.

3.4. Effects of sucrose and salt contents on penetration depth

The penetration depths of gellan gel with sucrose addition at 915 and 2450 MHz are shown in Fig. 8. The penetration depth values of microwave at 915 MHz were higher than those at 2450 MHz, which agreed with many research results that penetration depths decreased with increased frequency (Wang et al., 2003; Guan et al., 2004; Fennell and Boldor, 2013). Due to the decrease of dielectric constant with temperature for all samples at 915 MHz, the pattern of penetration depth with temperature was almost an opposite image of the pattern of loss factor shown in Fig. 4b. Increases of penetration depth with temperature were found for samples with different sucrose contents at 2450 MHz.

The effect of salt content on the penetration depth of gellan gel at 915 and 2450 MHz is shown in Fig. 9. At 915 MHz, the penetration depth of all samples decreased with temperature. The increase of salt content significantly reduced the penetration depth of gellan gel from 55.7 mm to 17.0, 10.1 and 7.8 mm at 100, 200, and 300 mM salt levels at 22 °C, respectively. The result could be attributed to the significant increase of loss factor with increasing salt

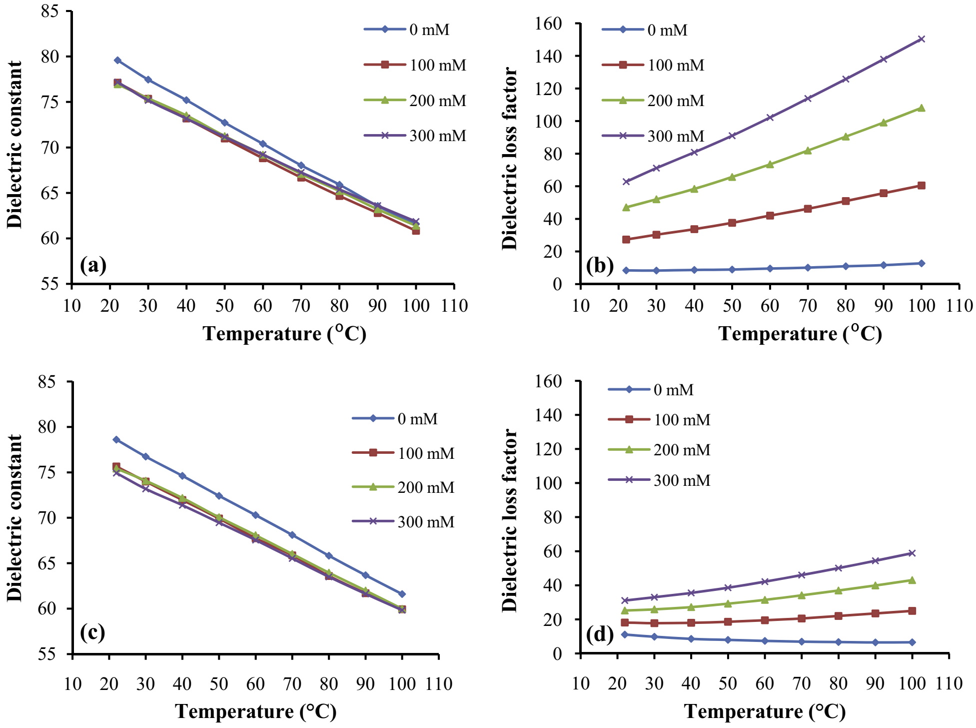

Fig. 7. Effect of salt content on the dielectric constant (a) and loss factor (b) of gellan gel at 915 (a and b) and 2450 (c and d) MHz between 22 and 100 °C.

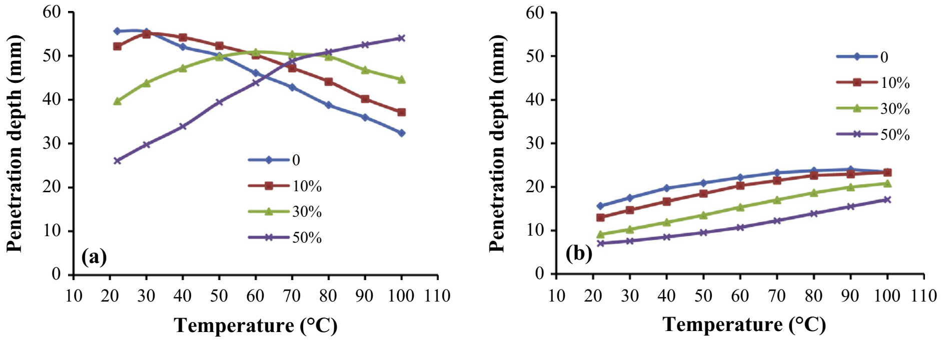

Fig. 8. Penetration depth of gellan gel with sucrose addition at (a) 915 MHz and (b) 2450 MHz between 22 and 100 °C.

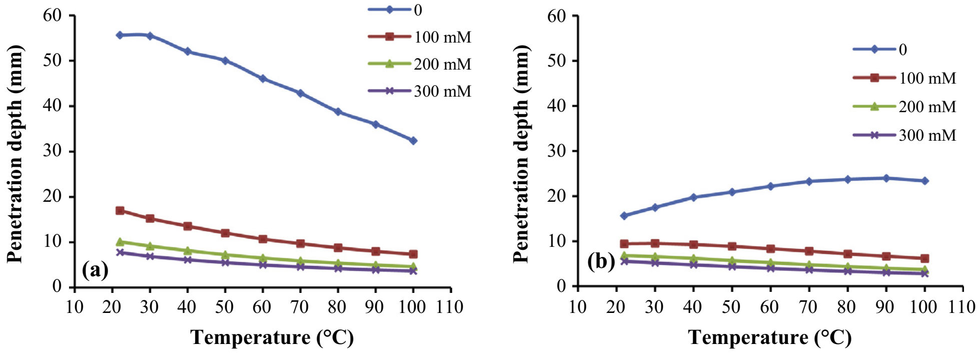

Fig. 9. Penetration depth of gellan gel with salt addition at (a) 915 MHz and (b) 2450 MHz between 22 and 100 °C.

content. The decrease of penetration depth with temperature was caused by the increase of loss factor while decrease of dielectric constant. Similarly, the penetration depth of gellan gel also decreased with salt content at 2450 MHz. However, an increase of penetration depth with temperature was found for gellan gels with no salt, while decreasing trends were found for all other samples (Fig. 9b).

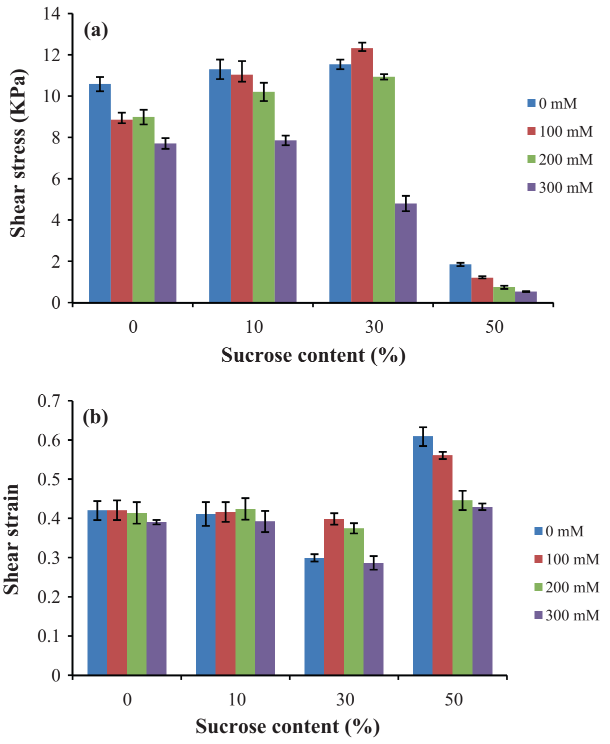

Fig. 10. Shear stress and shear strain at failure of gellan gel with various sucrose and salt contents at 22 °C.

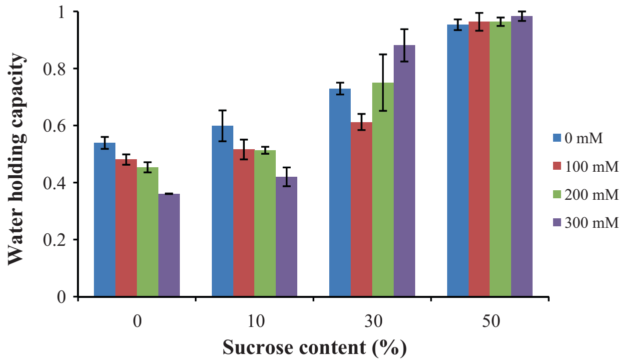

Fig. 11. Water holding capacity of gellan gel with various sucrose and salt addition at 22 °C.

3.5. Combined effects of sucrose and salt contents on gel strength

The combined effect of sucrose and salt content on gel strength of 1% gellan gel in terms of shear stress and shear strain at failure is shown in Fig. 10. The gel strength decreased with salt content at all sucrose levels except the gel with 10 mM salt and 0.3 g/mL (solution) sucrose, which presented the highest gel shear stress value. For samples with the same salt content, the shear stress of all samples increased with increasing sucrose content of up to 0.3 g/mL (solution), while the addition of 0.5 g/mL (solution) sucrose significantly decreased the gel strength. Many researches have been done to illustrate the importance of cations on the mechanism of gellan gel formation (Tang et al., 1994, 1995; Gibson and Sanderson, 1997). Tang et al. (2001) also reported the stabilizing effect of sucrose on gellan gel formation for packing the double gellan helices in the same way as cations. Morris et al. (2012) summarized in their review that high levels of sucrose promoted the association of gellan gel polymer chains by replacing most of the water in the gel-water mixture. The gel strength of 0.30, 0.75, and 1.2 wt% gellan gel was reported to increase with sucrose addition of up to 25% (Bayarri et al., 2002). However, when both cations and sucrose are presented in the gel network, optimum levels of both cations and sucrose are required for maximum gel strength. At cation concentration levels lower than the concentration to naturalize the negative charges of gellan polymer chain, the increase of sucrose strengthens the gel. However, when the cation level is high enough for gel formation and stabilization, the excess amount of sucrose will hinder the aggregation of gel network and thus weakens instead of strengthening the gel (Morris et al., 2012). Similar results were also found in the studies on 1% gellan gel with various Ca^{2+} (5–40 mM) and sucrose contents (15–35%) (Tang et al., 2001), and on 0.5% gellan gel with Ca^{2+} and 20%, 40%, and 60% sucrose (Sworn and Kasapis, 1998).

The result of maximum shear strain at failure which reflects the deformation of gellan gel at the point of fracture is shown in Fig. 10b. For samples with 0 or 0.1 g/mL (solution) sucrose, the shear strain of samples showed no significant difference regardless of salt content ($p > 0.05$). However, for gellan gels with 0.3 g/mL (solution) sucrose, salt addition of 0 or 300 mM resulted in significantly lower shear strain values ($p < 0.05$). The gels with 0.5 g/mL (solution) sucrose showed the highest shear strain values among all samples, indicating the highest gel extensities during deformation. The shear strain of the samples with 0.5 g/mL (solution) sucrose decreased with salt content, which might be caused by the weakening effect on the gel network by excess salt.

3.6. Combined effect of sucrose and salt content on water holding capacity

The combined effect of sucrose and salt addition on the water holding capacities of gellan gel is shown in Fig. 11. The water holding capacity of gellan gel with only 6 mM Ca^{2+} after centrifuge at 2000 rpm for 5 min was 0.54, which agreed with the result reported by Mao et al. (2001). The water holding capacities of gellan gels at all tested salt content levels increased with sucrose content, resulting in the highest water holding capacity values between 0.95 and 0.98 for samples with 0.5 g/mL (solution) sucrose. For the gellan gels with 0 or 0.1 g/mL (solution) sucrose addition, the water holding capacity values decreased with salt content. The results agreed with that reported by Mao et al. (2001) that the water holding capacity of 1% gellan gel decreased with the increase of Ca^{2+} concentration of up to 80 mM. However, the trend changed for samples with 0.3 g/mL (solution) sucrose where the water holding capacity first decreased for samples with 100 mM salt addition, and then increased with increasing salt contents. At 0.5 g/mL (solution) content level, no significant difference was found among the samples with different salt contents ($p > 0.05$).

4. Conclusions

The dielectric constant of 1% gellan gel (with 6 mM Ca^{2+}) increased with temperature while slightly decreased wtih frequency. The loss factor increased with temperature while decreased with frequency at frequencies lower than 0.9 GHz. The trend shifted to opposite at frequencies higher than 2.7 GHz. The addition of sucrose and salt both affected the dielectric properties of gellan gel. Adding sucrose significantly decreased the dielectric constant, while adding salt was more effective in the adjustment of dielectric loss factor values. Regression equations relating the dielectric properties with sucrose/salt content and temperature were developed, which can be used to calculate the specific formulation of a 1% gellan gel (including 6 mM Ca^{2+}) to obtain certain dielectric properties to match with the real foods to be processed in the 915 MHz MAP system. When using gellan gels as model foods for heating pattern determination, chemical markers will be added to the gel solution while it is cooled to a temperature close to the gelation temperature. The cold-set gellan gels will be packed and color change will take place following the temperature change at different locations during the MAP processes. The gels will then be cut into thin layers and the images will be taken and analyzed using the computer vision system. Results showed that the gel strength of gellan gel with sucrose addition of up to 0.3 g/mL (solution) was relatively high, indicating the gels strong enough for post process handling. Adding 0.5 g/mL (solution) sucrose resulted in much softer while highly deformable gels with the highest water holding capacity. This study well demonstrated the possibility of using gellan gel as a model food for microwave pasteurization processes. Moreover, due to the increasing use of gellan as a food additive worldwide, the knowledge on the physical properties of gellan gel can be useful for the relevant industrial applications.

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