

Medium-Chain Sugar Amphiphiles: A New Family of Healthy Vegetable Oil Structuring Agents

Swapnil R. Jadhav,[†] Hyeondo Hwang,[†] Qingrong Huang,[§] and George John^{*,†}

[†]Department of Chemistry, The City College of New York, and The Graduate School and University Center of The City University of New York, 160 Convent Avenue, New York, New York 10031, United States

[§]Department of Food Science, Rutgers, the State University of New Jersey, 65 Dudley Road, New Brunswick, New Jersey 08901, United States

S Supporting Information

ABSTRACT: Vegetable oils are frequently structured to enhance their organoleptic and mechanical properties. This is usually achieved by increasing the net amount of saturated and/or trans fatty acids in the oil. With the risk of coronary heart diseases associated with these fatty acids, the food industry is looking for better alternatives. In this context, the medium-chain dialkanoates of low-calorie sugars (sugar alcohol dioctanoates) are investigated as a healthy alternative structuring agent. Precursors of sugar amphiphiles, being FDA-approved GRAS materials, exhibited high cell viability at a concentration $\sim 50 \mu\text{g}/\text{mL}$. They readily formed nanoscale multilayered structures in an oil matrix to form a coherent network at low concentrations (1–3 wt %/v), which immobilized a wide range of oils (canola, soybean, and grapeseed oils). The structuring efficiency of sugar amphiphiles was computed in terms of mechanical, thermal, and structural properties and found to be a function of its type and concentration.

KEYWORDS: organogel, structured oil, structuring agent, sugar surfactants, self-assembly, medium-chain amphiphiles

■ INTRODUCTION

Growing awareness concerning human health has been continually fueling the need for (i) changing the dietary habits of consumers and (ii) developing *nutritionally balanced foods* that are appetizing and capable of promoting a healthy lifestyle as well.¹ Prolonged consumption of high calorific and fatty (saturated/trans fatty acids) products has been shown to elevate the risk of metabolic syndromes such as obesity, coronary heart disease, and diabetes.^{2–4} To mitigate the generally negative impact of lipid-rich products, several health organizations have called for improving the lipid profile of foods, that is, reducing saturated and eliminating trans fatty acids.⁵

Vegetable oil, a major source of vital lipids, constitutes an integral part of daily food products.⁶ It is generally incorporated in the semisolid form, commonly referred to as structured oil.⁷ Hydrogenation, interesterification, and addition of saturated fat are a few of the commercially employed structuring methodologies, which mainly focus on increasing the content of structuring components, for example, saturated and/or trans fatty acids.^{7,8} Thus, current methods do not conform to the above stated dietary requirements and potentially render structured oil unwholesome for consumption. However, structuring of oils is an important process from a product formulation perspective. Structuring of vegetable oil is a process that converts fluidic oil to a fat-like high-melting material. Structuring components, when incorporated into an oil phase, crystallize and form a colloidal polycrystalline fat network, which entraps oil and improves its mechanical and physical properties.^{9,10} It also enhances organoleptic properties (consistency, texture, flavor, and stability) of the oil and prevents its exudation from food products. Hence, conscious

efforts are being taken to develop alternative structuring methods with improved lipid profile, functionality, and performance compared with conventional methods.

The molecular gelation phenomenon enables conversion of the liquid state of a solvent to a solid state.^{11–13} When dispersed in the solvent matrix, molecular gelators (small amphiphilic molecules with molecular weight of $< 3 \text{ kDa}$) spontaneously self-assemble with the aid of intermolecular interactions to form a three-dimensional (3-D) network. The resulting network entraps the solvent molecules with the aid of capillary forces and forms a semisolid viscoelastic material—a gel. Due to mechanistic resemblance of the gelation phenomenon to a fat crystal network in entrapping liquid molecules, it has emerged as a potential alternative structuring process. Several molecular gelator systems (fatty alcohols, fatty acids, wax esters, monoglycerides, sorbitan alkylates, phytochemicals, etc.) have been explored for structuring of oils.^{10,14–18} Most of the systems, ironically, are composed of long-chain saturated fatty acids and do not impart additional nutritional value to the structured oil. Consequently, there is a strong urge to develop novel gelators that behave as an alternative and have been proven to exhibit no adverse effects on human health. To date, very few molecular gelators (phytochemical- and ceramide-based) with positive health effects have been developed.^{19,20}

In a continual effort to develop functional yet nutritional alternative structuring agents, we report a novel gelator system.

Received: May 6, 2013

Revised: October 29, 2013

Accepted: November 15, 2013

Published: November 15, 2013

Sugar alcohol-based gelators, namely, mannitol dioctanoate and sorbitol dioctanoate, have been proposed as potential food-grade and healthy structuring agents (Figure 1). These sugar

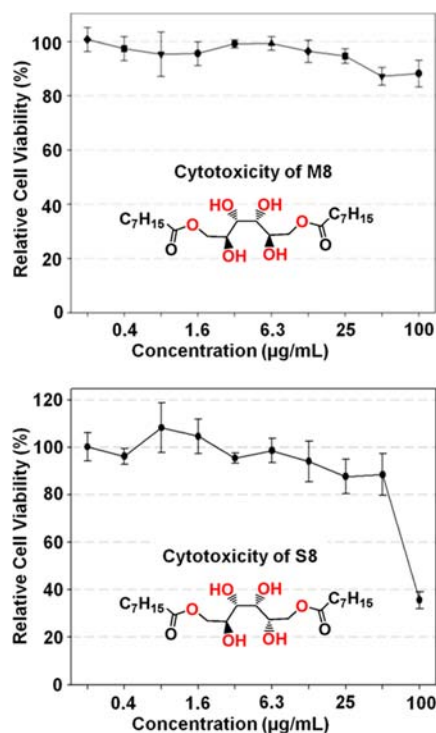


Figure 1. Molecular structures and cytotoxicity data of M8 and S8. Cytotoxicity was deduced in terms of cell viability that is plotted against gelator concentration (dissolved in DMSO).

dioctanoates essentially consist of two octanoic acid chains (C8) appended to a sugar alcohol molecule through lipase-labile ester bonds. The building blocks of these gelators — sugars and octanoic acid—offer physiological advantages which are favorable for developing foods that will not elevate the risk of metabolic syndromes. Compared to typical sugars, sugar alcohols are nonreducing and have low caloric/glycemic indices.²¹ Octanoic acid is a type of medium-chain fatty acid that is nonhypercholesterolemic and does not easily re-esterify to form triglycerides, accounting for high plasma clearance in the body.²²

MATERIALS AND METHODS

Materials. Refined vegetable oils were purchased from a local supermarket: canola oil (ConAgra Foods, Inc.), olive oil (Wakefern Food Corp.), soybean oil (USDA), and grapeseed oil (Wakefern Food Corp.). Human hepatocellular carcinoma cells (HepG2) were generously provided by Dr. Mou-Tuan Huang, Department of Chemical Biology, Rutgers, The State University of New Jersey. Minimum essential medium (MEM), fetal bovine serum (FBS), phosphate-buffered saline (PBS), 100× penicillin, streptomycin, 0.25% trypsin with ethylenediaminetetraacetic acid (EDTA), and RPMI-1640 media were all purchased from Fisher Scientific. 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) was obtained from Sigma-Aldrich. Mannitol dioctanoate (M8) and sorbitol dioctanoate (S8) were enzymatically synthesized as described in our previous literature (please refer to the Supporting Information for details).^{23,24}

Cytotoxicity Assay. The cytotoxicity of amphiphiles was assessed by the microculture MTT reduction assay on HepG2 cells.²⁵ This assay is based on the reduction of a soluble tetrazolium salt by the

mitochondrial dehydrogenase of the viable cells to form an insoluble colored product, formazan. The amount of formazan formed can be measured spectrophotometrically after dissolution of the dye in DMSO. The activity of the enzyme and the amount of the formazan produced is proportional to the number of cells alive. Reduction of the absorbance value is attributed to the killing of cells or inhibition of cell proliferation by amphiphiles.

HepG2 cells were seeded in 96-well plates at a density of 10000 cells per well in a final volume of 100 µL of cell culture medium. A stock solution of M8 and S8 was prepared in DMSO. On the second day, the stock solutions were diluted to different concentrations (0.1–100 ppm) and incubated with HepG2 cells for 24 h. Untreated cells were used as a control. Subsequently, cell culture media were removed and cells were incubated with 100 µL of RPMI-1640 medium containing 0.5 mg/mL MTT for 2 h at 37 °C. MTT solution was then carefully aspirated, and the formazan crystals formed were dissolved in 100 µL of DMSO in each well. Light absorbance at 560 and 670 nm was recorded with a plate reader (Synergy HT, Biotek). Relative cell viability was expressed as $A_{560}-A_{670}$ normalized to that of the untreated wells. Data are presented as the mean ± standard deviation with four well repeats.

Preparation of Vegetable Oil Gels. Gel samples were prepared by adding the desired weight percentage of M8 or S8 (1–5 wt %/v based on oil) in the oil. The heterogeneous mixture of gelator and oil was heated to 130 °C for M8 (or to 70 °C for S8) to produce sol. The sol was held at this temperature with continuous agitation for 10 min to remove any self-assembly history of gelator molecules. The sol was cooled to room temperature to form gels. Prior to characterization of gel samples for structural, thermal, and mechanical properties, they were aged for 7 days at room temperature (25–30 °C) unless a given set of experiments necessitated different aging durations.

Characterization of Vegetable Oil Gels. Gelation efficiency of gelators was determined in terms of minimum gelation tendency (MGC) and gel-to-sol transition temperature (T_{gel}). Gelation mechanism was studied by performing XRD and optical microscopy. Standard protocols were employed for characterization, the details of which are given in the Supporting Information.

Rheological Measurements. Dynamic rheological measurements were performed on a stress-controlled rheometer (AR 2000 ex) with a cone and plate geometry (1° 58' 47" angle and 40 mm diameter with a truncation gap of 45 µm). About 1 mL of gel was loaded on the plate, and the cone was lowered to a specified truncation gap. Precautions were taken to minimize shear-induced disruption of gel network. Before measurements, samples were equilibrated within the geometry for 10 min. Excess gel was trimmed from the periphery of cone, ensuring optimal filling. Yield strain, σ_y , was deduced by performing oscillatory strain sweep measurements from 0.02 to 100% deformation at a fixed frequency of 1 Hz. Oscillatory frequency sweep measurements were performed in the frequency domain of 0.01–10 Hz with a constant strain of 0.1%, which is within the linear viscoelastic regime of the sample. All of these experiments were done at 25 °C and repeated twice.

RESULTS AND DISCUSSION

Cytotoxicity of M8 and S8. The determination of toxicity of sugar alcohol-derived gelators is imperative as they are being investigated for edible applications such as structuring of vegetable oils. Hence, the cytotoxicity of M8 and S8 was initially tested against HepG2 cells by using a MTT-based cell viability assay (the greater the cell viability, the higher the biocompatibility). Figure 1 illustrates the concentration-dependent cell viability of M8 and S8. The cells exhibited ~83% viability up to a concentration of 50 µg/mL of gelators. When their concentration was increased to 100 µg/mL, the gelators behaved differently. The cytotoxicity of M8 was not affected even at 100 µg/mL. In contrast, a steep increase in cytotoxicity was observed for S8, and the cell viability decreased to 35% at 100 µg/mL. The dissimilarity in degree of

biocompatibility can be attributed to the type of sugar present in the headgroup, because it is the only difference between the gelators. However, the FDA has categorized mannitol and sorbitol as generally recognized as safe (GRAS) chemicals, and their LC_{50} (oral LC_{50} rat) values are almost comparable at 15000 mg/kg.²⁶ Thus, the exact reason for the acute behavior of S8 is unclear. Nonetheless, it can be believed that the sugar alcohol gelators are biocompatible at moderate dose concentration.

Gelation of Vegetable Oils: Efficiency and Self-Assembly Mechanism. The efficiency and versatility of M8 and S8 were examined by using a wide range of vegetable oils such as olive oil (OO), canola oil (CO), soybean oil (SO), and grapeseed oil (GO). The results are summarized in Table 1.

Table 1. Vegetable Oil Gelation Efficiency and Versatility of M8 and S8

oil ^a	M8		S8	
	MGC ^b	<i>d</i> -spacing (nm)	MGC ^b	<i>d</i> -spacing (nm)
olive	G (1.0)	2.94	TG (3.0)	2.45
canola	G (1.0)	2.95	TG (3.0)	2.41
soybean	G (1.3)	2.95	TG (3.0)	2.42
grapeseed	G (1.3)	2.92	TG (3.0)	2.42

^aOils are arranged in increasing order of unsaturation in their triglyceride profile. ^bValues in parentheses are MGCs of corresponding gelator (wt %/v, mg/100 mL). MGC is defined as minimum amount of gelator (g) required for forming a volume filling and solvent entrapping 3-D network in 100 mL of given solvent. G, opaque gel; TG, translucent gel.

Both M8 and S8 displayed excellent gelation tendency in all of the tested oils. Furthermore, all of the gels were stable for months. The gelation efficiency of M8 and S8, in terms of MGC, was found to be independent of the type of oil used for making gels.

MGC values of mannitol-derived amphiphile were 2-fold lower than those of the sorbitol analogue; that is, MGCs of M8 and S8 were ~1.3 and 3.0 wt %/v respectively. The M8 gels were opaque in appearance, whereas S8 gels were translucent (Figure 2). The morphology of M8 gels consisted of micrometer-sized fibers, which are densely packed to form a 3-D network, thereby explaining the opaqueness of oil gels (Figure 2A). The network of S8 gels consisted of thin needle-like microcrystallites along with a few clusters of microcrystallites randomly dispersed in an oil matrix (Figure 2B). Thus, the stereochemical difference (difference in the orientation of only one hydroxyl group) between mannitol

and sorbitol was found to markedly affect the vegetable oil gelation capabilities of these gelators.

X-ray diffraction (XRD) analysis was performed on oil gels and on the neat samples of corresponding gelators. Pure M8 and S8 have been reported to exhibit well-ordered multilayered stacking patterns with periodicity, that is, long *d*-spacing, of 2.96 and 2.38 nm for M8 and S8, respectively (Figure 3A,C).^{23,24} XRD spectra of oil gels showed primary peaks close to the periodicity of corresponding neat samples; for M8 gels it was ~2.95 nm, and for S8 gels it was ~2.42 nm (Figure 3B,D). Moreover, the long *d*-spacing values were found to be independent of the type of oils, suggesting that the type and composition of oil had no significant effect on the mode of self-assembly of gelator molecules (Table 1). Unpublished data and a previous study on volatile solvent gels of M8,²⁴ where XRD analysis of xerogels was possible, indicate that the self-assembly pattern and periodicity of the gelator molecule is similar in gel and neat solid state. Due to such similarity in the XRD data, it is hypothesized that M8/S8 exhibit similar multilayered stacking in the oil matrix as well. Self-assembly is driven by intermolecular hydrogen bonding between the hydroxyl groups and van der Waals forces between the alkyl chains. These fibers undergo lateral aggregation with each other, thereby forming a volume-filling 3-D network. Owing to the noncovalent nature of interactions involved in the self-assembly process, the network is transient and is responsive toward external stimuli such as temperature and shear.

Structuring Efficiency of Gelators: Canola Oil as a Model Vegetable Oil. The sugar gelators and gelation phenomenon were further investigated for their potential application as structuring systems for vegetable oils. Henceforth, for simplicity, the terms “structured oils” and “oil gels” will be used interchangeably. CO was used as a model vegetable oil for studying the structuring efficiency of sugar gelators. CO is widely recognized for its nutritional attributes. It contains the lowest level of saturated fatty acid (~7% of total fatty acid amount), whereas the unsaturated fatty acid content is very high. It is an excellent source of ω -6 and ω -3 fatty acids. Hence, it is one of the major oils consumed in the United States for household and industrial applications.

The CO structured using M8/S8 was analyzed for its morphology and thermal and mechanical properties. The morphology of network and the thermal behavior (melting profile) of the structured oil dictate its organoleptic properties. The presence of crystalline fiber network imparts palatable texture, whereas a large melting range (10–15 °C) results in a dislikeable greasy mouth sensation of structured oil. The morphology was studied by using an optical microscope, and

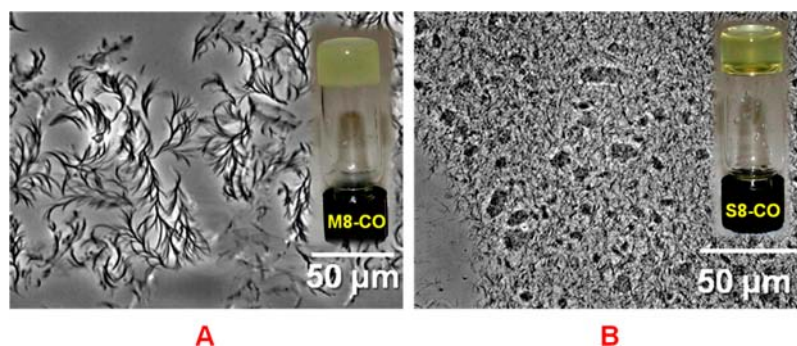


Figure 2. Photographs and optical microscope images of grapeseed oil gels (5 wt %/v): (A) M8 gel; (B) S8 gel.

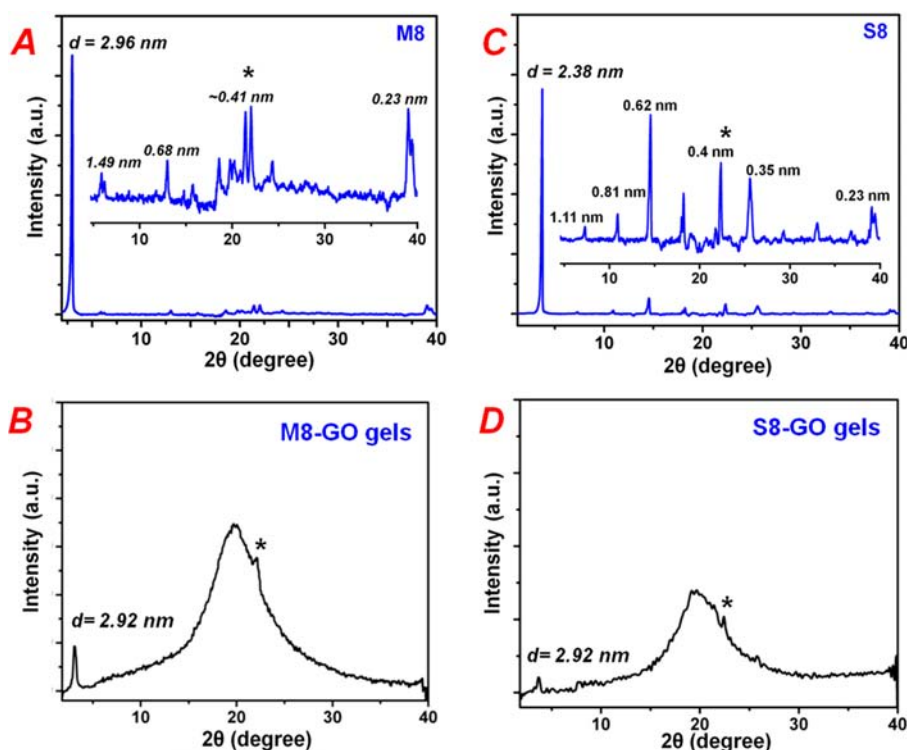


Figure 3. (A) X-ray diffraction (XRD) pattern of a neat M8 sample; (B) XRD pattern of grapeseed oil sample of M8 (M8-GO, 5 wt %/v); (C) XRD pattern of a neat S8 sample; (D) XRD pattern of grapeseed oil sample of S8 (S8-GO, 5 wt %/v). The X-ray diffractograms of neat samples (both M8 and S8) exhibit patterned spacing of peaks, which is a characteristic of multilayered stacking of amphiphiles. *d*-spacing values of GO gels samples were similar to their corresponding gelator samples. Moreover, a characteristic signal of hexagonal subcell packing of hydrocarbon chains in the self-assembled lipids was found in both neat and GO gel samples of both M8 and S8 (Bragg's peak at ~0.4 nm, which is denoted by *). Both of these observations indicate that the gelators self-assemble in similar patterns (well-ordered lamellar structures) in neat as well as in gel samples.

the thermal property was computed in terms of gel-to-sol transition temperature (T_{gel}). Mechanical strength governs the firmness, consistency, and processing ability of structured oil. Dynamic oscillatory rheology was performed to determine various mechanical factors such as (i) G' (elastic modulus, measure of firmness), (ii) G'' (viscous modulus, measure of liquidity), and (iii) σ_y (strain amplitude at which G' sharply decreases and the two moduli cross each other, measure of gel stiffness). Effects of parameters such as concentration of gelators, aging of gels, and continuous application of small deformation on the properties of structured oil were examined.

Effect of Concentration of Gelators. An oscillatory strain sweep measurement showed that for all of the M8-CO gels G' greatly predominated G'' during the linear viscoelastic region (i.e., where G' and G'' values do not change appreciably). For example, M8-CO gel (5 wt %/v) exhibited a linear region until 0.1% strain. Over this region, the value of G' exceeded that of G'' by ~8 times (Supporting Information Figure S1A). More importantly, the yield strain (σ_y) values of gels increased with the concentration of M8; σ_y for 1% gel was 2.39, whereas σ_y for 5% gel was 4.09 (Table 2). " σ_y " signifies a point beyond which the three-dimensionality of the gel network is destroyed and the gel behaves more like a viscous liquid. Thus, it can be inferred that the stiffness and firmness (i.e., overall strength) of gel are functions of the concentration of M8.

The increment in the firmness of CO gels was also observed in the frequency sweep measurements (Figure 4). Irrespective of the M8 concentration, G' exceeded G'' over the entire experimental frequency range, which is a typical response of gels. At low concentration of M8 (1 wt %/v), G' exhibited

Table 2. Mechanical, Thermal, and Structural Data Obtained for CO Gels with Various Concentrations of M8 and S8

amount (wt %/v)	σ_y^a (%)	G'^b (Pa)	G''^c (Pa)	T_{gel}^d (°C)	morphology
M8					
1	2.39	247	83	79–82	fibrous
3	3.13	2052	426	99–103	
5	4.09	4300	1176	109–111	
S8					
3	0.49	449	132	45–49	microcrystallites
5	1.26	2093	485	59–61	

^aYield strain, defined as the applied strain value at G'/G'' crossover.

^bAverage value of elastic modulus in the linear viscoelastic region.

^cAverage value of viscous modulus in the linear viscoelastic region.

^dGel-to-sol transition temperature of gels measured by adopting the inversion tube method.

slight dependency on higher frequency, indicating that the 1% gel may lose its elastic nature on application of shear at high frequencies for an extended period of time. However, with increase in gelator concentration the G' progressively became more independent, and for 5% gels it was constant over the entire range. As in the case of σ_y , G' was also observed to increase with the concentration of gelator. The G' value of the 5% gel was 4300 Pa, which is 2-fold higher than that of the 3% gel (2052 Pa) and 17-fold higher than that of the 1% gel (247 Pa). The level of G' characterizes the firmness of the gel.

The improvement in the gel strength with gelator concentration was attributed to the enhancement of density of the 3-D network (solid content). Higher content of gelator

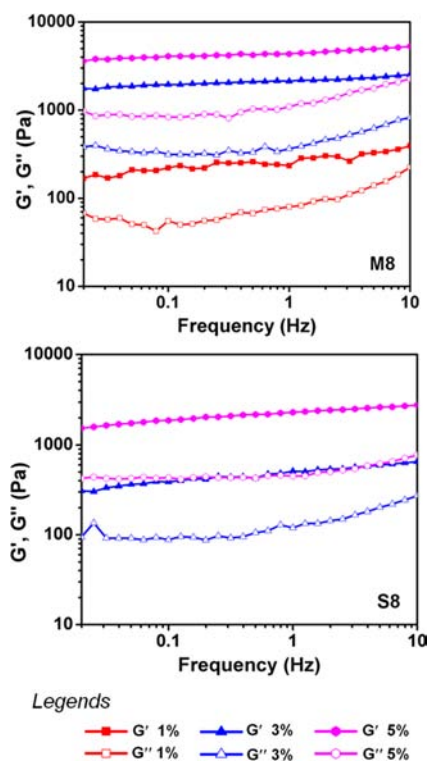


Figure 4. Concentration-dependent rheological measurements (oscillatory frequency sweep) of M8-CO gels and S8-CO gels.

in the oil causes higher degree of supersaturation and hence nucleation sites, which in turn boost the number and length of self-assembled fibers. As a result, more fibers and entanglement exist in a unit area of the network. Such enrichment of the network makes the gel stronger and amplifies the rheological parameters (G' and σ_y). Analysis of optical microscope images of the gels corroborates the above hypothesis (Supporting Information Figure S1B). The 1% gel exhibited few fibrous structures, which were loosely connected to form a network. As the M8 content was raised to 3 and 5%, the fiber density and network compactness both progressively increased, thereby improving the gel strength. Like mechanical properties, the thermal property (T_{gel}) of gels was also found to be greatly influenced by the gelator concentration. More importantly, the M8-based CO gels exhibited a melting profile over a relatively narrow temperature range. The complete list of rheological and T_{gel} data is presented in Table 2.

Similarly, in the case of S8-CO gels, the mechanical and thermal properties of CO gels were found to be proportional to the S8 concentration. The values of elastic modulus (G'), yield strain (σ_y), and T_{gel} were enhanced several-fold by increasing the amount of gelator in the oil (Table 2). The S8 gels, too, exhibited a narrow gel-to-sol transition range. The strain sweep measurements showed the usual dominance of G' over G'' in the linear viscoelastic region (Supporting Information Figure S2A). For S8-CO gels, as in case of M8-CO gels, the linear region was found to be up to 0.1% strain. The frequency sweep measurements exhibited negligible dependency of G' over the entire frequency range, confirming their gel-like state (Figure 4). Increment in the concentration of S8 in gels from 3 to 5% improved the density of microcrystallites and increased the number of clusters of microcrystallites, thereby leading to strengthening of gels (G' and σ_y were increased by factors of 5 and ~ 3 , respectively) (Supporting Information Figure S2B).

In addition to the analogous concentration-dependent behavior of M8 and S8 gels, a more striking observation was the difference in the properties of gels with the same concentration of M8 and S8. At a given gelator concentration, the M8 gels were found to be much stiffer with higher yield strain values as compared to S8 gels. For instance, G' and σ_y values for 5% M8 gels were greater than those of 5% S8 gels by at least a factor of 3. The gel-to-sol transition temperatures were also relatively higher for M8 gels, 109–111 °C for 5% M8 gels compared to 58–61 °C for 5% S8 gels. Thus, it can be inferred that the subtle difference in the stereochemistry of the sugar group markedly affects the self-assembly mechanism, which in turn greatly influences the gelation efficiency and gel properties of sugar alcohol gelators. Such influence of differing molecular structures will allow for modulation of gel properties and development of structured vegetable oil as per the requirement of an application.

Effect of Aging on Properties of Structured Oil. The structured vegetable oils are widely used in food products that may or may not have long shelf lives. It is always desired that the properties of the structured oil remain the same or do not change considerably when stored for a long period of time. In other words, the network of structuring agents should not change temporally. However, many gel systems, especially polymer gels, are known to undergo morphological transformations over a period of time. Either the self-assembled structures of the gel network are entirely changed or the network is spatially rearranged to a thermodynamically stable state. In such a scenario, the aged gels exhibit different properties compared to the fresh ones. To check the morphological transformations in the case of M8 and S8, their CO gels (5 wt %/v concentration) were aged for different time lengths and analyzed for their mechanical, structural, and thermal properties. Figure 5 represents the rheological response of M8 and S8 gels on aging for 1, 7, and 30 days.

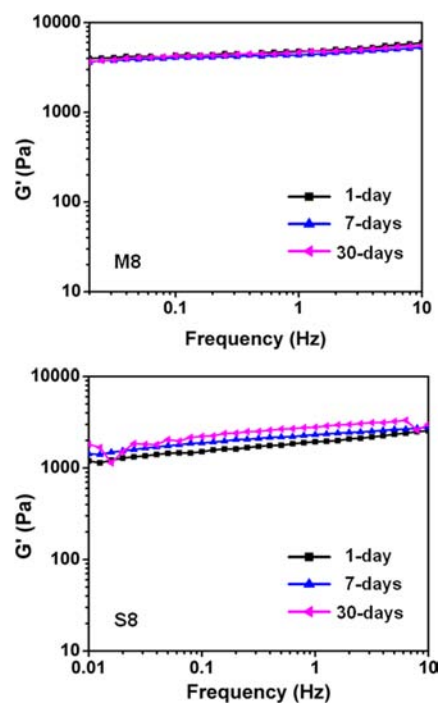


Figure 5. Effect of aging on the rheological properties of M8-CO gels (5 wt %/v) and S8-CO gels (5 wt %/v).

Frequency sweep measurements of M8 gels (Figure 5) indicate that their rheological responses are alike. For all three samples, G' (~ 4400 Pa) and σ_y ($\sim 3.17\%$) were found to be similar (Table 3), which can be interpreted as the firmness and

Table 3. Mechanical, Thermal, and Structural Data Obtained for CO Gels (5 wt %/v) Aged over Different Time Scales

aging (days)	G' (Pa)	G'' (Pa)	σ_y (%)	T_{gel} ($^{\circ}\text{C}$)	morphology
M8					
1	4579	1534	3.17	108–111	fibrous
7	4300	1176	4.09	109–111	
30	4460	1514	3.17	110–112	
S8					
1	1761	572	0.46	58–61	microcrystallites
7	2093	485	1.26	59–61	
30	2444	699	2.5	59–61	

stiffness (overall gel strength) remaining the same. Similarly, the thermal properties of gels (T_{gel}) did not show any variations with aging duration. Such identical responses of M8 gels stem from the ability of M8 to form thermodynamically stable self-assembled structure as soon as the M8-CO sol is cooled. The thermodynamic stability of the aggregates inhibits further transformation or rearrangement of the network. Optical micrographs support the above arguments, as they show that the morphology of the gel aged for 30 days is identical to that of the gel aged for 7 days (Supporting Information Figure S3).

In contrast to M8-CO gels, S8-CO gels exhibited slight dependency on aging period. The gel strength was found to increase, although marginally, with aging duration (Figure 5 and Table 3). G' and σ_y progressively increased by factor of 1.26 and 2, respectively. Morphological analyses of these gels did not exhibit noticeable transformations in the self-assembled microcrystalline structures of S8 (Supporting Information Figure S4). Thus, the enhancement in the mechanical properties of S8 gels could be attributed to the spatial rearrangement of aggregates to increase the lateral interactions, thereby improving the compactness of the network.

Effect of Prolonged Small Deformation on Vegetable Oil Gels. Oscillatory time sweep experiments facilitate inspection of any macro- or microstructural changes a gel may undergo when subjected to a constant shear for a long time. The structured oils are frequently processed in other food products, where they are continuously deformed to achieve uniform dispersion in the food matrix. In addition, these experiments substantiate the effect of aging on the rheological behavior of gels. Thus, the CO gels of M8 and S8 were analyzed for time-dependent rheological properties. A constant strain (0.1%) was applied on gels at a frequency of 1 Hz over a period of 50 min. As depicted in Figure 6, both M8 and S8 gels exhibit excellent uniformity in the rheological response; elastic and viscosity moduli remained constant for both gel samples. These results indicate that the gels do not undergo any structural changes on application of continuous deformation.

Effect of the Type of Oil on Gelation Efficiency of Sugar Gelators. Finally, the effect of different oils on the gelation efficiency of M8 and S8 was studied by investigating their mechanical and thermal properties. Oils selected for the study exhibit various amounts of unsaturations in their triglyceride profile. OO and CO are high in monounsaturated FA (oleic acid) content. SO contains high amounts of mono-

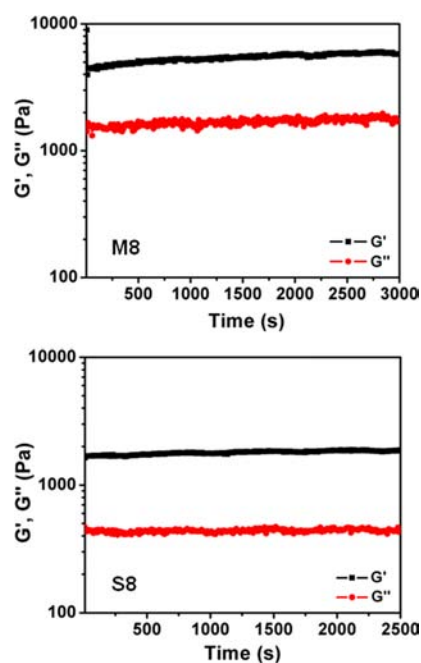


Figure 6. Oscillatory time sweep measurements of canola oil gels of M8 and S8 (5 wt %/v).

and diunsaturated FA (linoleic acid), whereas GO predominantly contains di- and triunsaturated FA (linolenic acid). Because of these variations, these oils differ in their physical properties such as melting point, polarity, and dissolving power, which indicates that the type of oils may affect the structuring ability of the agent. However, in the present case, it was found that the self-assembly mechanism and morphology of M8 and S8 are independent of oil type (Table 1). Hence, the bulk properties of gels are also expected to follow a similar trend.

Irrespective of the type of oil, the gel firmness (G') was found to be of similar magnitude for 5 wt %/v oil gels of M8 (~ 4000 Pa) and S8 (~ 2000 Pa) (Supporting Information Figures S5 and S6). Moreover, the profiles of G' and G'' were similar over the entire experimental frequency range (0.01–10 Hz), indicating that in addition to gel firmness the viscoelastic behavior of different oil gels was equivalent as well. Similar to rheological responses, the thermal properties exhibited a similar trend. The T_{gel} range of OO, SO, and GO gels was narrow and on par with that of CO gels; T_{gel} of M8 gels was ~ 108 – 111 $^{\circ}\text{C}$ and T_{gel} of S8 gels was 59 – 61 $^{\circ}\text{C}$. Thus, it can be inferred that in the case of sugar alcohol gelators, the properties of oil gels are an exclusive function of the type and concentration of gelators used for gelation of oils.

In summary, the developed sugar alcohol dioctanoates M8 and S8 were shown to be efficient vegetable oil structuring agents. The biocompatibility of the gelators was confirmed by conducting cytotoxicity studies, which indicated negligible toxicity of M8 and S8 and high cell viability at concentrations as high as 50 $\mu\text{g}/\text{mL}$. M8 and S8 effectively structured a range of vegetable oils at very low concentrations (1–3 wt %/v). The mechanical, structural, and thermal properties of the structured oil were found to be a function of the type and concentration of sugar alcohol gelator employed for structuring. Compared to S8, M8 was more efficient in structuring vegetable oils. The gel strength (G' and σ_y) of M8 oil gels was always found to be greater than that of S8 oil gels by several times. M8 self-assembled in oils to form dense fibrous structures and

consequently produced opaque gels. On the other hand, S8 self-assembled in oils to form loosely connected micro-crystallites and produced translucent gels. Such significant variations in oil gels resulting from the subtle changes in the chemical structure of gelator will enable modulation of gel properties and develop structured vegetable oil as per the requirement of an application.

■ ASSOCIATED CONTENT

● Supporting Information

Details of synthesis, gelation characterization experiments (XRD, microscopy, T_{gel}); additional figures and tables pertaining to gelators' efficiency as oil structuring agents. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*(G.J.) E-mail: john@sci.ccnycunyc.edu. Phone: +1 (212) 650-8353. Fax: +1 (212) 650-6107.

Funding

This work was partially supported by GoMRI Grant SA 12-05/GoMRI-002 (subcontract TUL-626-11/12), NSF-CBET (Rapid) Grant 1046099, and PSC-CUNY awards to G.J. Q.H. received financial support from a U.S. Department of Agriculture National Research Initiative (2009-35603-05071).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the Chemical Engineering Department of CCNY and Prof. Alexander Couzis for granting permission to extensively use the rheology laboratory.

■ ABBREVIATIONS USED

M8, mannitol dioctanoate; S8, sorbitol dioctanoate; MGC, minimum gelation concentration; T_{gel} , gel-to-sol transition temperature; XRD, X-ray diffraction; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; HepG2, human hepatocellular carcinoma cells; 3-D, three dimensional; CO, canola oil; OO, olive oil; SO, soybean oil; GO, grapeseed oil

■ REFERENCES

- (1) Vaclavik, V. A.; Christian, E. W. *Essentials of Food Science*, 3rd ed.; Springer: New York, 2008.
- (2) Lee, L.; Alloosh, M.; Saxena, R.; Van Alstine, W.; Watkins, B. A.; Klaunig, J. E.; Sturek, M.; Chalasani, N. Nutritional model of steatohepatitis and metabolic syndrome in the Ossabaw miniature swine. *Hepatology* **2009**, *50*, 56–67.
- (3) Katan, M. B.; Zock, P. L.; Mensink, R. P. Trans fatty acids and their effects on lipoproteins in humans. *Annu. Rev. Nutr.* **1995**, *15*, 473–493.
- (4) Aro, A.; Jauhiainen, M.; Partanen, R.; Salminen, I.; Mutanen, M. Stearic acid, trans fatty acids, and dairy fat: effects on serum and lipoprotein lipids, apolipoproteins, lipoprotein(a), and lipid transfer proteins in health subjects. *Am. J. Clin. Nutr.* **1997**, *65*, 1419–1426.
- (5) Krauss, R. M.; Deckelbaum, R. J.; Ernst, N.; Fisher, E.; Howard, B. V.; Knopp, R. H.; Kotchen, T.; Lichtenstein, A. H.; McGill, H. C.; Pearson, T. A.; Elaine Prewitt, T.; Stone, N. J.; Van Horn, L.; Weinberg, R. Dietary guidelines for healthy American adults: a statement for health professionals from the Nutrition Committee, American Heart Association. *Circulation* **1996**, *94*, 1795–1800.

- (6) Gunstone, F. D., Ed. *Vegetable Oils in Food Technology: Composition, Properties and Uses*, 2nd ed.; Blackwell Publishing (Wiley): Oxford, UK, 2011.

- (7) Floeter, E.; Bot, A. Developing products with modified fats. In *Improving the Fat Content of Foods*; Williams, C. M., Buttriss, J., Eds.; Woodhead Publishing: Cambridge, UK, 2006; pp 411–427.

- (8) Gunstone, F. D., Ed. *Modifying Lipids for Use in Food*; Woodhead Publishing: Cambridge, UK, 2006.

- (9) Dassanayake, L. S. K.; Kodali, D. R.; Ueno, S. Formation of oleogels based on edible lipid materials. *Curr. Opin. Colloid Interface Sci.* **2011**, *16*, 432–439.

- (10) Perneti, M.; van Malssen, K. F.; Floeter, E.; Bot, A. Structuring of edible oils by alternatives to crystalline fat. *Curr. Opin. Colloid Interface Sci.* **2007**, *12*, 221–231.

- (11) Weiss, R. G.; Terech, P., Eds. *Molecular Gels: Materials with Self-assembled Fibrillar Networks*; Springer: Dordrecht, The Netherlands, 2006.

- (12) Raghavan, S. R. Distinct character of surfactant gels: a smooth progression from micelles to fibrillar networks. *Langmuir* **2009**, *25*, 8382–8385.

- (13) John, G.; Balachandran, V. S.; Jadhav, S. R.; Vemula, P. K. Biorefinery: a design tool for molecular gelators. *Langmuir* **2010**, *26*, 17843–17851.

- (14) Marangoni, A. G. Organogels: an alternative edible oil-structuring method. *J. Am. Oil Chem. Soc.* **2012**, *89*, 749–780.

- (15) Rogers, M. A. Novel structuring strategies for unsaturated fats – meeting the zero-trans, zero-saturated fat challenge: a review. *Food Res. Int.* **2009**, *42*, 747–753.

- (16) Marangoni, A. G.; Garti, N., Eds. *Edible Oleogels: Structure and Health Implications*; AOCS Press: Urbana, IL, USA, 2011.

- (17) Floeter, E. Structuring oils without highly saturated fats – how far are we? *Eur. J. Lipid Sci. Technol.* **2012**, *114*, 983–984.

- (18) Lupi, F. R.; Gabriele, D.; Facciolo, D.; Baldino, N.; Seta, L.; de Cindio, B. Effect of organogelator and fat source on rheological properties of olive oil-based organogels. *Food Res. Int.* **2012**, *46*, 177–184.

- (19) Bot, A.; Agterof, W. G. M. Structuring of edible oils by mixtures of γ -oryzanol with β -sitosterol or related phytosterols. *J. Am. Oil Chem. Soc.* **2006**, *83*, 513–521.

- (20) Rogers, M. A.; Wright, A. J.; Marangoni, A. G. Oil organogels: the fat of the future? *Soft Matter* **2009**, *5*, 1594–1596.

- (21) Friedman, R. B. Monosaccharides and polyols in foods. In *Glycoscience: Chemistry and Chemical Biology*, 2nd ed.; Fraser-Reid, B. O., Tatsuta, K., Thiem, J., Eds.; Springer: Berlin, Germany, 2008; pp 841–856.

- (22) Akoh, C. C. Structured lipids. In *Food Lipids—Chemistry, Nutrition, and Biotechnology*, 2nd ed.; Akoh, C. C., Min, D. B., Eds.; Dekker: New York, 2002; pp 877–908.

- (23) Jadhav, S. R.; Vemula, P. K.; Kumar, R.; Raghavan, S. R.; John, G. Sugar-derived phase-selective molecular gelators as model solidifiers for oil spills. *Angew. Chem., Int. Ed.* **2010**, *49*, 7695–7698.

- (24) Jadhav, S. R.; Chiou, B.-S.; Wood, D. F.; Degrande-Hoffman, G.; Glenn, G. M.; John, G. Molecular gels-based controlled release devices for pheromones. *Soft Matter* **2011**, *7*, 864–867.

- (25) Mitra, R. N.; Shome, A.; Paul, P.; Das, P. K. Antimicrobial activity, biocompatibility and hydrogelation ability of dipeptide-based amphiphiles. *Org. Biomol. Chem.* **2009**, *7*, 94–102.

- (26) MSDS of mannitol and sorbitol (Sigma-Aldrich).