Addition of Sugars Influences Color of Oil-in-Water Emulsions

Jochen Weiss* and Wayne Liao

Colloidal and Interfacial Food Science Laboratory, Department of Food Science and Technology, University of Tennessee, Knoxville, Tennessee 37996

The influence of glucose, fructose, lactose, and glycerol on the color and appearance of surfactant-stabilized oil-in-water emulsions containing a red dye was investigated. A stabilized (Tween-20) oil-in-water emulsion was diluted into sugar solutions to give a range of oil droplet and sugar concentrations. Tristimulus coordinates (L, a, b) and reflectance spectra were measured using a spectrophotometer. With increasing sugar concentration, reflectance spectra shifted to lower reflectance values. Tristimulus coordinates were reduced by approximately 50% for emulsions containing high concentrations of sugar. Adding fructose to emulsions reduced L, a, b values more significantly than adding glucose, lactose, or glycerol. Tristimulus coordinates remained constant when the temperature was raised from 20 to 80 °C. The experimental results were explained in terms of the change of relative refractive index at the water−oil interface. The results have important implications for the food industry as they offer a new means to control and optimize the color of food emulsions.

Keywords: *Emulsion; color; spectral reflectance; light scattering; sugar*

INTRODUCTION

Many food products exist in the form of emulsions: e.g., cheese, milk, salad dressings, sauces, and beverages (Weiss et al., 1996). Emulsions are dispersed systems that consist of two or more immiscible liquids with one liquid being dispersed in the other in the form of droplets (Dickinson, 1992; McClements, 1999). Customer acceptance of food emulsions depends on a large number of factors such as color, appearance, taste, smell, and texture (Birch et al., 1977; Jellinek, 1985; Lawless and Heymann, 1998). Color and appearance are usually the first qualities to be perceived and thus may have a stronger impact on product acceptance than other parameters. A better understanding of the parameters that influence the optical properties of food emulsions will enable food manufacturers to better design and control the color of such products.

Many studies have been conducted on the origin, perception, and characterization of color (Wyszecki and Stiles, 1967; MacAdam, 1981; McLaren, 1983; Berger-Schunn, 1994). It is well-known that changes in color of food materials can be related to the kinetics of chemical or biochemical reaction: for example, the formation of brown/black pigments via the Maillard reaction, the change of color of myoglobin in the presence or absence of oxygen, or the browning of vegetable matter due to enzymatic reactions (Fennema, 1996). Changes in the physical state and structure of a food product can alter the color of a system as well. Variation in pH, for example, can alter the structure of meat. As a consequence, the color of the meat product is altered despite the fact that pigment levels remain constant (Fletcher, 1999). Although the presence, nature, and chemical composition of natural and synthesized food colorants and dyes in a large variety of foods have been intensively studied (Mackinney and Little, 1962; Francis and Clydesdale, 1975; Hutchings, 1994; Burdock, 1997), only a few experiments have been conducted on the color of food emulsions.

The color of an emulsion depends on the interaction of emulsion droplets with light waves: i.e., reflection, transmission, absorption, and scattering. These interactions are determined by the nature of the electromagnetic radiation (wavelength, intensity, and incident angle), the characteristics of emulsion droplets (size, concentration, and refractive index), and the colorants present (absorption spectra and concentration) (McClements, 1998). Chantrapornchai and coauthors investigated in two separate studies the influence of droplet and dye characteristics on optical properties of oil-in-water emulsions (Chantrapornchai et al., 1999a, 1999b). They found that both dye and droplet concentration greatly influence the color of oil-in-water emulsions. The spectral reflectance decreases with increasing dye concentration and decreasing droplet concentration. Spectral reflectances increased with decreasing droplet sizes. The influence of droplet characteristics on color of oil-in-water emulsions containing different types of dye was similar (Chantrapornchai et al., 1999a, 1999b). Physical phenomena such as mass transport processes that alter droplet characteristics can change the color of emulsions; e.g., Ostwald ripening in low-molecular-weight hydrocarbon emulsions with small droplet sizes significantly changed the optical properties of emulsions (Weiss and McClements, 2000). McClements recently developed a theoretical model to predict the color of emulsions based on the Kubelka−Munk solution of the general radiation theory (McClements et al., 1998). The model can predict tristimulus coordinates and reflectance spectra of emulsions with small droplet sizes and low oil droplet concentrations.

In a previous yet-unpublished study, we investigated the influence of sugar on the aging of oil-in-water

* To whom correspondence should be addressed. Telephone: (865) 974-2753. Fax: (865) 974-2750. E-mail: jweiss1@utk.edu.

10.1021/jf000418g CCC: $19.00
Published on Web 09/15/2000

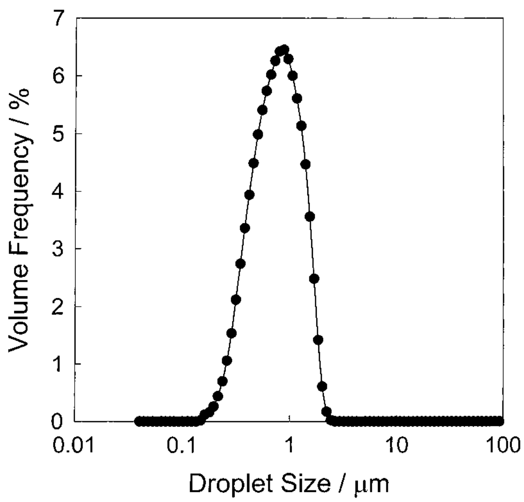

Figure 1. Droplet-size distribution of 10 wt % mineral-oil-in-water emulsion.

emulsions. During these experiments, we observed that the addition of sugar reduced the turbidity of emulsions. The emulsion had a color that was "less white". We hypothesized that the addition of sugar changed the optical properties of the water phase in such a way that scattering and absorption of light are strongly reduced. Adding different solutes to the aqueous phase of emulsions could thus prove to be a valuable means to control and design the color of food emulsions.

The purpose of this present study is to determine how the addition of sugars and the subsequent change in optical properties of the aqueous phase influence color and spectral reflectance of oil-in-water emulsions.

MATERIALS AND METHODS

Materials. Mineral oil (ρ = 840 kg/m3, η_0 = 0.05 Pas), polyoxyethylene (20) sorbitanmonolaureate (Tween 20), glucose, lactose, fructose, and glycerol were obtained from Sigma Chemical Company (St. Louis, MO). A red food colorant (FD&C Red No. 40) was obtained from Hilton Davis (Cincinnati, OH). Distilled, deionized water was used to prepare all solutions and emulsions. We used nonfood grade mineral oil as opposed to commercially available edible oil to ensure that the dispersed phase was free of colorant. Tween 20 is a certified food emulsifier with a critical micellar concentration of 0.0006 g/L and an average molecular weight of 1.228 kg/mol (Schick, 1967).

Emulsion Preparation. An aqueous surfactant solution was prepared by dissolving 2 wt % Tween 20 in water. Mineral oil (10 wt %) and surfactant solution (90 wt %) were then homogenized in a high-speed blender (Waring Products Division, New Hartford, CT) to form a coarse premix. Emulsion premixes were further homogenized using a high-pressure valve homogenizer (University of Tennessee, Knoxville, TN) to obtain a stock emulsion with a unimodal droplet size distribution and a mean droplet diameter of 1.05 μm. The droplet size distribution of the stock emulsion is shown in Figure 1. The stock emulsion was then diluted into sugar solutions containing either 0% or 0.02% FD&C Red 40, to give a series of emulsions that had oil concentrations ranging from 0.005 to 0.1 wt % and sugar concentrations ranging from 0 to 30 wt %. All solutions were freshly prepared from the stock emulsion prior to each measurement. The stock emulsion was stored for no longer than one week at 23 °C (± 1 °C). The droplet-size distribution of the stock emulsion was analyzed every day to ensure that droplet sizes remained constant for all experiments.

Droplet-Size Characterization. A laser diffraction instrument (LS 230, Beckman Coulter Corporation, Miami, FL) was used to measure the droplet-size distribution of emulsions. Emulsions were diluted into distilled water (<0.01 wt %) prior to analysis to avoid multiple scattering effects. A relative refractive index of 1.098 (refractive index of oil/refractive index of aqueous phase) was used to calculate the droplet-size distribution (Hiemenz and Rajagalopan, 1997). Droplet size measurements are reported as mean diameter: $\bar{d} = \sum n_i d_i / \sum n_i$, where n_i is the number of droplets of volume-based diameter d_i. Droplet sizes were measured three times to reduce statistical errors.

Absorbance Measurements. Absorbance of dye solutions was measured using a UV−visible diode array spectrophotometer (HP 8452A, Hewlett-Packard Co., Wilmington, DE). A quartz cuvette with a 1-cm path length contained the samples during measurements. Distilled water was used to calibrate the instrument prior to conducting measurements. Spectra were recorded over a wavelength range of 200 to 800 nm. The diode array detector of the spectrophotometer acquired spectral data at all wavelengths simultaneously and absorbance spectra were calculated using a Fast-Fourier Transform method.

Refractive Index Measurements. The refractive indices of mineral oil and aqueous sugar solutions were measured using a standard refractometer (LR 45227, Milton Roy, Ivyland, PA). The temperature of solutions during measurements was adjusted from 23 to 80 °C (±0.2 °C) using a cryogenic water bath (F25, Julabo USA Inc., Kutztown, PA).

Color and Spectral Reflectance Measurements. The color and spectral reflectance of emulsions were measured using a spectrophotometer with an integrated-sphere setup (CM 508d, Minolta Co., Ramsey, NJ). The spectral reflectance of the emulsions was measured relative to a barium sulfate ($BaSO_4$) standard white plate. A fixed amount of emulsion sample was poured into a measurement cup. The sides of the measurement cup were painted black and the cup was covered with the above-mentioned standard white plate before the measurement was carried out. In addition, color values were determined using daylight (D65, 2°) as a standard light source. The spectrophotometer represents the color of the samples in terms of the three-dimensional *L*, *a*, *b* color space system. In the *L*, *a*, *b* color space, +*L* is the white direction, -*L* is the black direction, +*a* is the red direction, -*a* is the green direction, +*b* is the yellow direction, and -*b* is the blue direction (Wyszecki and Stiles, 1967).

RESULTS

Absorbance of Dye Solution. To determine the concentration of the dye that was to be used in subsequent experiments, absorption spectra of solutions of FD&C Red 40 ranging in concentration from 0.005 to 0.05 wt % were measured (graph not shown). Absorption spectra of all red dye solutions had a single broad absorption peak at λ_{max}500 nm. The dye concentration was directly proportional to the absorption at λ_{max} for dye concentrations smaller than 0.025 wt %. The relationship became nonlinear for dye concentrations larger than 0.03 wt %. A 0.02 wt % dye solution had a maximum absorption of 1.0 and was chosen as the standard dye concentration for all subsequent experiments. The adsorption spectrum of 0.02 wt % dye solution is shown in Figure 2.

Influence of Oil-Droplet Concentration on Optical Properties of Emulsions. Prior to the investigation of the influence of sugar type and concentration on color of emulsions, we investigated the influence of the oil droplet concentration on optical properties of emulsions by measuring the spectral reflectances and tristumulus coordinates of a series of oil-in-water emulsions containing a range of oil droplet concentrations (0.005−0.1 wt %). The spectral reflectance of both dye-free (Figure 3a) emulsions and emulsions containing

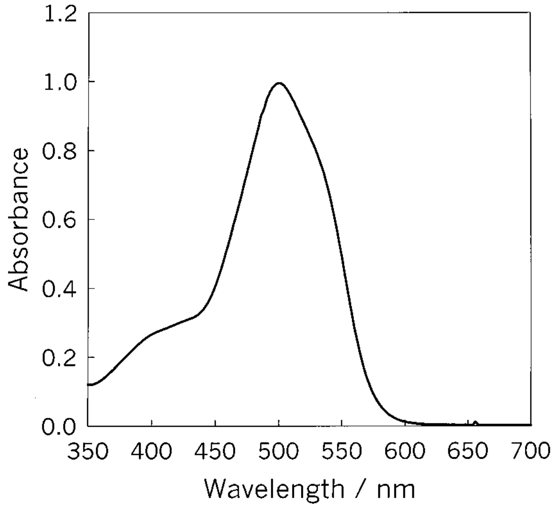

Figure 2. Absorbance spectra of 0.02 wt % red dye solution (FD&C 40) between 350 and 700 nanometers.

0.02 wt % dye (Figure 3b) depended strongly on the oil droplet concentration. Reflectance values decreased initially as oil droplet concentration decreased; that is, the reflectance of 0.1 wt % emulsion at 400 nm was about five times larger than the reflectance of 0.025 wt % emulsion (Figure 3). Reflectance values were lowest at oil droplet concentration of approximately 0.025 wt %. Spectral reflectance values increased for emulsions with oil concentrations of less than 0.025 wt %.

Oil droplet concentration of mineral oil emulsions influenced *L*, *a*, *b* tristimulus coordinates as well (Figure 4). Of the three color coordinates, the *L*-value or "lightness" of emulsions was most strongly affected by particle concentration (Figure 4a). *L*-values for both dye-containing and dye-free emulsions had minima at oil droplet concentration of 0.02 wt %, which corresponded to the minima encountered in the reflectance spectra–oil droplet concentration relationship (Figure 3). The effect of oil-droplet concentration on *a* and *b*-values was less pronounced (Figure 4b and c). Dye-free emulsions had maxima in *a* and *b*-values at 0.02 wt % oil as opposed to having minima in the presence of 0.02 wt % dye.

Influence of Glucose Concentration on Optical Properties of Emulsion. The influence of solute concentration on the color of emulsions was investigated by dispersing increasing amounts of glucose in the aqueous phase of mineral oil emulsions. Figure 5 illustrates the change in reflectance spectra of emulsions containing 0.1 wt % mineral oil with increasing glucose concentrations (0 to 30 wt %). Increasing the glucose concentration decreased spectral reflectance values of both dye-free (Figure 5a) and dye-containing emulsions (Figure 5b).

The change in color of mineral oil-in-water emulsions caused by the presence of glucose in the aqueous phase was influenced by the oil concentration as well. *L*, *a*, and *b* values of emulsions with increasing glucose concentration (0 to 30 wt %) are shown as a function of oil droplet concentration in Figure 6. The influence of glucose concentration on all three tristimulus coordinates was most pronounced at high oil concentration; i.e., the *L*-value decreased by approximately 50% at 0.1 wt % (Figure 6a). *L*, *a*, and *b* values plotted as a function of oil droplet concentration had minima whose location depended on the sugar concentration; i.e., 30 wt %

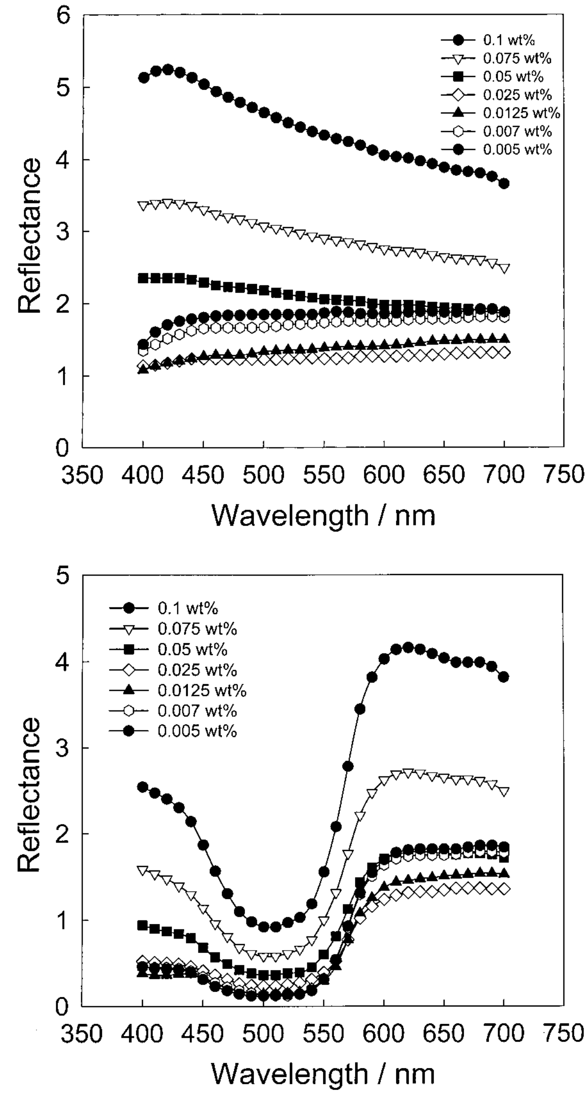

Figure 3. Reflectance spectra of 1 μm mineral-oil-in-water emulsions containing a range of oil concentrations (0.005–0.1 wt %): (a) without red dye, (b) containing 0.02 wt % red dye.

glucose *a*-values were lowest at 0.06 wt % oil, whereas 0 wt % glucose *a*-values were lowest at 0.02 wt % oil (Figure 6b). Slight inconsistencies in *b*-values can be attributed to systematic errors and the fact that absolute *b*-values did not change as significantly as *L* and *a*-values (Figure 6c). It should be noted that the mean droplet-size distribution of emulsions containing sugars did not significantly increase during the course of the experiment; i.e., the mean droplet size increased by less than 2% (data not shown). The long-term stability of emulsions containing large quantities of sugar, however, may be reduced, e.g., due to osmotic effects. A separate study on the long-term stability of oil-in-water emulsions containing sugars is currently being conducted in our laboratory.

Influence of Molecular Structure of Solutes on Optical Properties of Emulsions. The influence of the molecular structure of solutes on the color of oil-in-water emulsions was examined by dispersing lactose, glucose, and fructose in the aqueous phase of emulsions. In addition, glycerol, a common solvent for suspensions of solid particles, was used. Figure 7 illustrates the change in *L*, *a*, and *b* values as influenced by the molecular structure of the solute. Below solute concentrations of 20 wt %, the tristimulus coordinates were

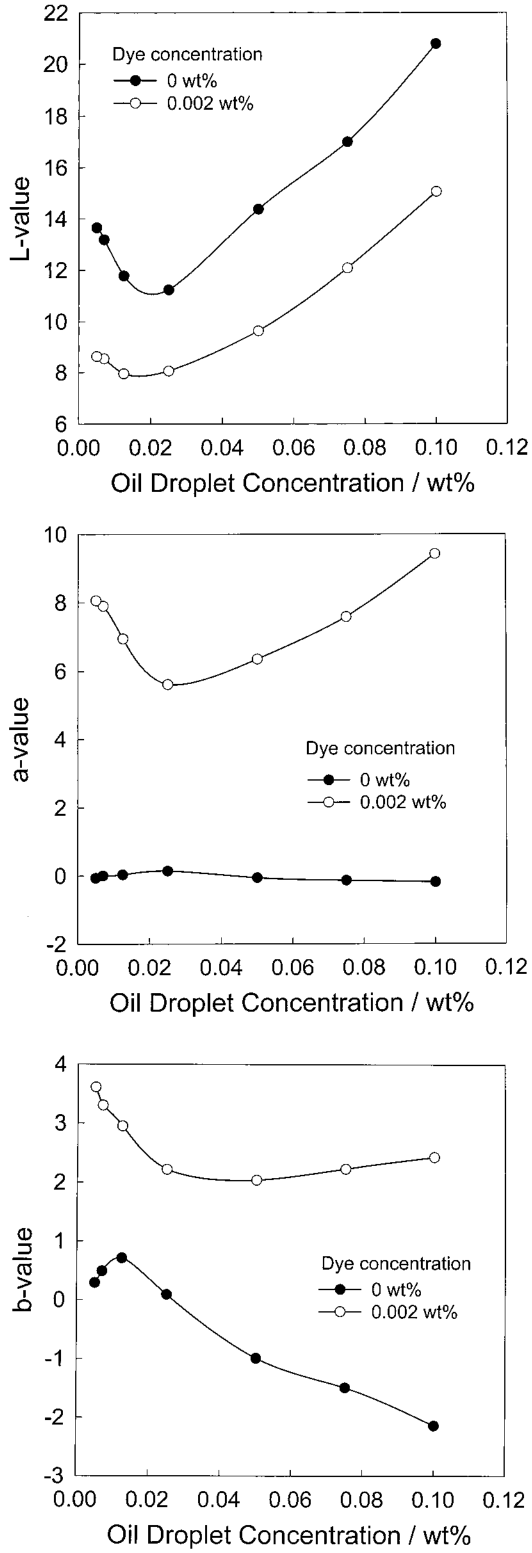

Figure 4. Tristimulus coordinates [(a) *L*-value, (b) *a*-value, and (c) *b*-value] of solute-free oil-in-water emulsions as a function of oil droplet concentration. Emulsions shown contain either 0 wt % dye or 0.02 wt % dye.

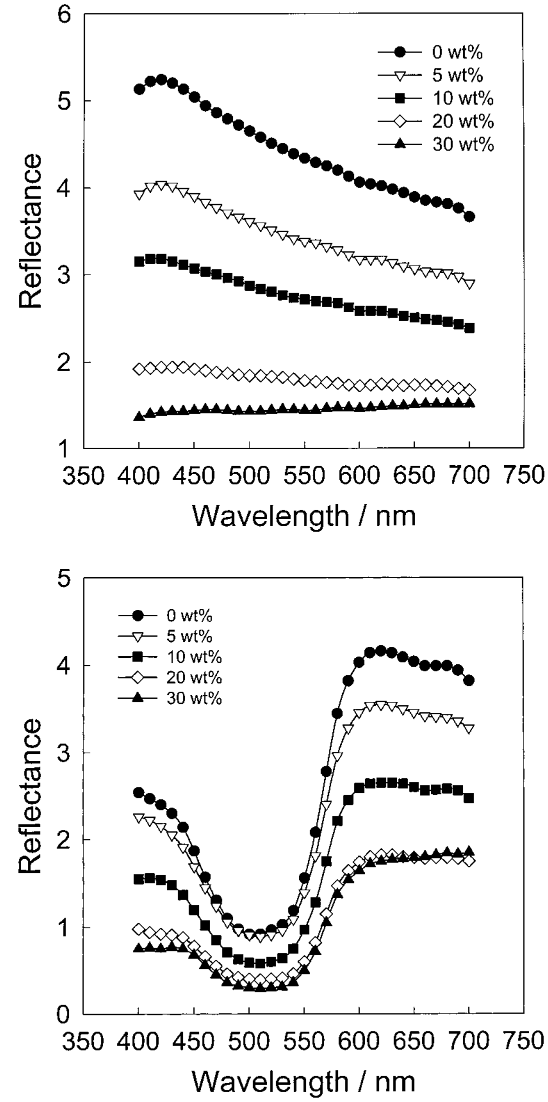

Figure 5. Reflectance spectra of 0.1 wt % oil-in-water emulsions containing glucose dispersed in the aqueous phase at concentrations ranging from 0 wt % to 30 wt %: (a) without dye, (b) 0.02 wt % red dye.

largely unaffected by the type of solute that was used. Above 20 wt %, a slight dependence of *L*-values on the molecular structure of the solvent was observed (Figure 7a); *a* and *b*-values were only marginally influenced by the type of solute used in the experiments (Figure 7b and 7c).

Influence of Temperature on Optical Properties of Emulsions. The temperature of 0.1 wt % mineral oil-in-water emulsions containing 0 to 30 wt % glucose was raised from 20 to 80 °C in 10 °C steps. Measurements of absorption spectra at these temperatures did not show any change (results not shown).

DISCUSSION

Influence of Oil Concentration on Color of Emulsions. The influence of oil concentration on the color of emulsions in Figure 3 can be explained in terms of scattering and adsorption effects (Hapke, 1993). At high oil concentration, the particles backscatter a large portion of the incident light waves, thus increasing the reflectance values. At intermediate oil concentration backscattering is reduced. In addition, light is selectively absorbed by the emulsion droplets and is therefore not reflected back to the detector. At very low oil concentrations, scattering and adsorption are greatly reduced because of the lack of scattering bodies. The electromagnetic radiation can penetrate the sample and is then reflected by the standard white plate located on top of the sample. This explains the increase in *L*-values that can be seen at small oil concentration. Color measurements using a black glass plate as background at low

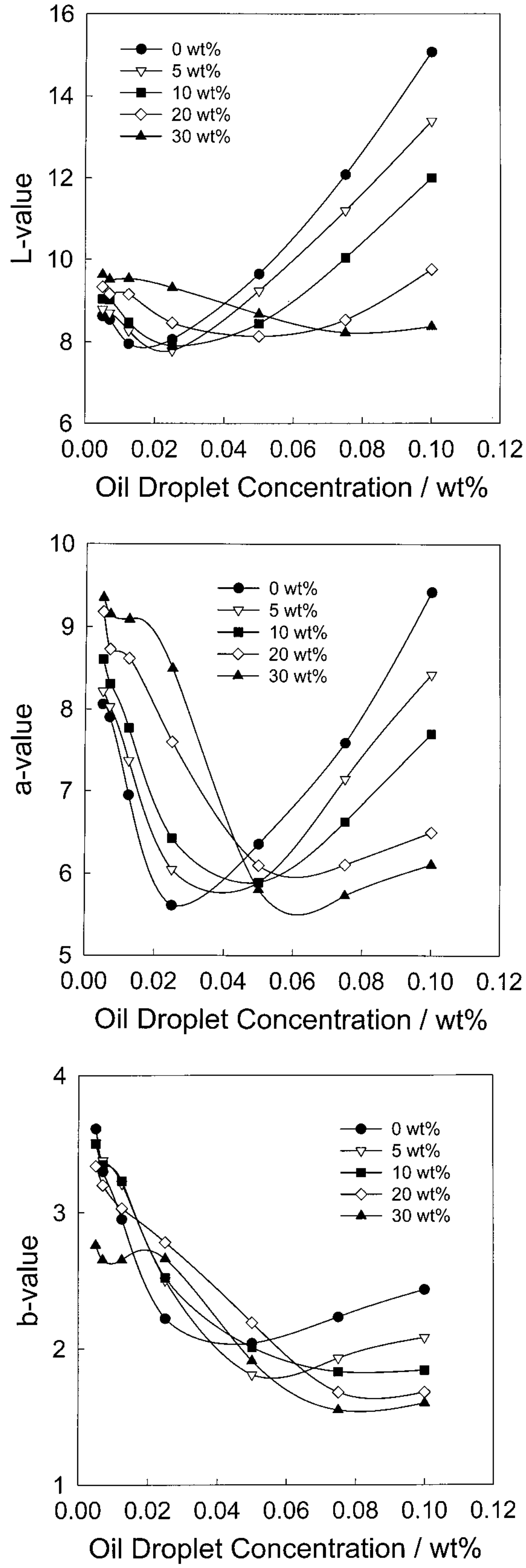

Figure 6. Tristiumulus coordinates [(a) *L*-value, (b) *a*-value, and (c) *b*-value] of oil-in-water emulsions with 0.02 wt % red dye containing 0 to 30 wt % glucose and 0.005 to 0.1 wt % oil.

oil concentrations were not feasible, because all of the light was absorbed by the black plate and not backscattered to the sensor. The results obtained in this part of

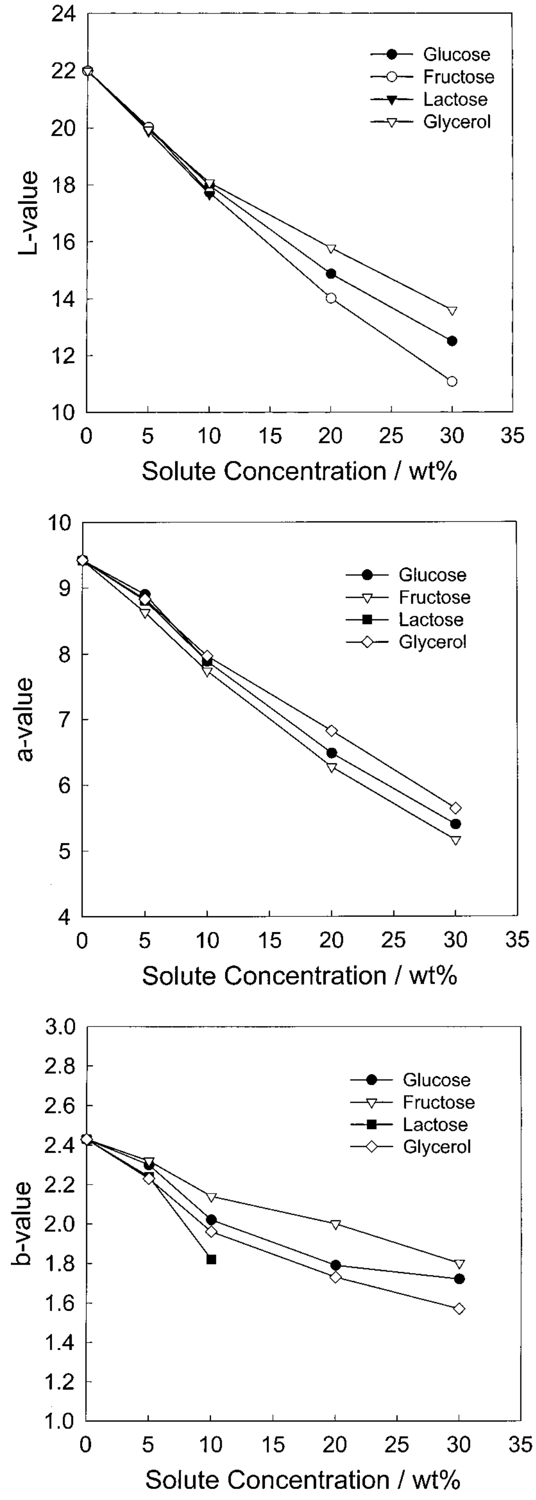

Figure 7. Tristiumulus coordinates [(a) *L*-value, (b) *a*-value, and (c) *b*-value] of 0.1 wt % oil-in-water emulsions containing different amounts of glucose, fructose, lactose, and glycerol (0–30 wt %) dispersed in the aqueous phase.

the study confirmed experimental values obtained by Chantrapornchai and coauthors (Chantrapornchai et al., 1999a).

Influence of SoluteConcentration on Color of Emulsions. To explain the influence of solutes such as sugars on the color of emulsions, the physical phenomena that determines the interaction between light and dispersed particles has to be examined. The correct mathematical description of light-scattering phenomena is extremely complex and hence only some special solutions to common light-scattering equations will be discussed. A more advanced discussion of light-scattering theory can be found elsewhere (Bohren and Huffman, 1983; Kokhanovsky, 1999). A light beam that propagates through a random medium containing particles that are capable of scattering and absorbing part of the electromagnetic wave will be attenuated after traversing a distance dl. The change in intensity I of the electromagnetic wave is given as

$$dI = N\pi r^2 Q_{ext} I dl \qquad (1)$$

where N is the number concentration of particles, r the particle radius, and Q_{ext} is the extinction efficiency. The extinction efficiency is a sum of absorption and scattering efficiencies, which both depend on wavelength, radius of particles, angle of observation, and relative refractive index. Several approximate solutions have been obtained; i.e., Rayleigh derived a solution for nonabsorbing particles with sizes that are considerably smaller than the wavelength of light. Debye extended Rayleighs solution to incorporate particle sizes in and above the wavelength of light (Hiemenz and Rajagalopan, 1997). Emulsion droplets are particles that partially absorb light and thus neither one of the above-mentioned solutions is applicable. Van de Hulst (Hulst, 1957) developed an expression for the extinction efficiency of partially absorbing spheres with a relative refractive index close to one:

$$Q_{ext} = 2 - 4e^{-\rho \tan \beta}\left(\frac{\cos \beta}{\rho}\right) \sin (\rho - \beta) - 4e^{-\rho \tan \beta}\left(\frac{\cos \beta}{\rho}\right)^2 \cos (\rho - 2\beta) + 4\left(\frac{\cos \beta}{\rho}\right)^2 \cos 2\beta \qquad (2)$$

where ρ is the so-called real parameter

$$\rho = 2x(n_{Re} - 1) \qquad (3)$$

with $x = 2\pi r/\lambda$ a size parameter and λ the wavelength of light. The parameter $\tan \beta$ can take values between 0 and ∞ and is defined as

$$\tan \beta = \frac{n\mathrm{I_m}}{n\mathrm{R_e} - 1} \qquad (4)$$

where n_{Im} is the imaginary part and n_{Re} the real part of the complex relative refractive index at the phase boundary between the particle and surrounding media. For nonabsorbing spheres, β simply becomes 0 and eq 2 reverts to the equation used by Chantrapornchai and coauthors in their study (Chantrapornchai et al., 1999a). Although eq 2 can only be applied to spheres with a relative refractive index close to one, the equation can be used to draw a number of important conclusions to observations made in this study. As more and more sugar is added to the aqueous phase of emulsions, the relative refractive index at the phase boundary changes. Because the properties of the oil droplets remain constant, it can be assumed that only the real part of the relative refractive index will be influenced by the addition of sugar. As indicated by McClements and coauthors in their study, the imaginary part of the refractive index of emulsion droplets is very small compared to the real part of the refractive index (McClements et al., 1998). Thus, we calculated Q_{ext} from eq 2 using a mean droplet diameter of 1 μm and a β of 0° for n_{Re} ranging from 1.08 to 1.02 (Figure 8). Figure 8 shows that as the relative refractive index approaches 1, the extinction coefficient as a function of the wavelength shifts to lower values, indicating that less light is scattered and absorbed by particles.

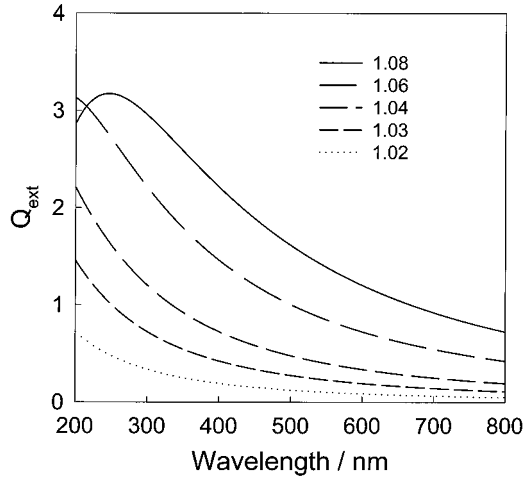

Figure 8. Extinction efficiency Q_{ext} as a function of wavelength calculated from eq 2 with relative refractive indices ranging from 1.08 to 1.02 ($r = 1$ μm, $\beta = 0°$).

To compare the above-mentioned theory to data obtained in this study, we measured the absolute refractive indices of dispersed phase and continuous phase containing increasing amounts of glucose at 23 °C. A refractometer with a polarized light source having a wavelength of 600 nm was used to obtain refractive indices of glucose solutions. Results are shown in Table 1. With increasing glucose concentration the absolute refractive index of the water phase increases from 1.3325 at 0 wt % glucose to 1.3805 at 30 wt % glucose. The relative refractive index, which is equal to the absolute refractive index of the oil phase divided by the absolute refractive index of the water phase, thus decreases. This confirms the hypothesis that smaller refractive indices caused by the addition of glucose do indeed reduce scattering and absorption, thereby lowering spectral reflectances.

Light scattering theory can also be used to explain changes in tristimulus coordinates (Figure 6). The tristimulus coordinates are directly related to spectral reflectance. L, a, and b values can simply be calculated from the observed reflectance spectra R of the sample (Hutchings, 1994)

$$L = 10Y^{0.5} \qquad (5)$$

$$a = \frac{17.5(1.02X - Y)}{Y^{0.5}} \qquad (6)$$

$$b = \frac{7.0(Y - 0.847Z)}{Y^{0.5}} \qquad (7)$$

where

$$X = k \int_{380}^{710} RE\bar{x} d\lambda \qquad (8)$$

$$Y = k \int_{380}^{710} RE\bar{y} d\lambda \qquad (9)$$

$$Z = k \int_{380}^{710} RE\bar{z} d\lambda \qquad (10)$$

k is a constant chosen such that $Y = 100$ for a perfect white; $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the CIE standard observer

Table 1. Refractive Indices of Glucose, Fructose, Lactose, and Glycerol Solutions as a Function of Solute Concentration

solute concentration (wt %)	solute			
	glucose	fructose	lactose	glycerol
0	1.3325	1.3325	1.3325	1.3330
5	1.3400	1.3400	1.3400	1.3387
10	1.3470	1.3475	1.3470	1.3455
20	1.3630	1.3650	*a*	1.3600
30	1.3805	1.3900	*a*	1.3675

[a] Maximum solubility reached.

Table 2. Refractive Indices of Glucose Solutions (0−30 wt %) and Mineral Oil as a Function of Solute Concentration

temperature (°C)	glucose concentration (wt %)					mineral oil
	0	5	10	20	30	
23	1.3325	1.3400	1.3470	1.3630	1.3805	1.4630
30	1.3320	1.3390	1.3465	1.3625	1.3795	1.4620
40	1.3310	1.3375	1.3450	1.3610	1.3780	1.4590
50	1.3290	1.3360	1.3435	1.3595	1.3765	1.4560
60	1.3275	1.3345	1.3420	1.3575	1.3745	1.4530
70	1.3250	1.3320	1.3400	1.3540	1.3720	1.4510
80	1.3240	1.3310	1.3385	1.3525	1.3700	1.4480

functions; and E is the emission spectra of the illuminant. The strong decrease in L values with increasing glucose concentrations at higher oil concentrations (Figure 6a) can thus be explained in terms of the dependence of L, a, and b values on the reflectance spectra. As the refractive index approaches 1 the extinction efficiency decreases more strongly (eq 2). Because the spectral reflectance is directly proportional to the number of droplets that are dispersed in the aqueous phase and the extinction efficiency (eq 1), the effect is more pronounced at higher oil concentrations.

Influence of Molecular Structure on Color of Emulsions. On the basis of the previously discussed light scattering theory, we can now explain the small differences that are observed in measurements of L, a, and b values of glucose, lactose, fructose, and glycerol solutions at solute concentrations larger than 20 wt %. Table 1 shows the increase in refractive index of sugar and glycerol solutions with increasing solute concentrations. The absolute refractive index of fructose solution at 30 wt % solute concentration is slightly higher than the refractive index of glucose and glycerol at 30 wt %. At high solute concentration spectral reflectances of fructose solutions are consequently smaller than spectral reflectances of glucose or glycerol solutions. Lactose could not be compared to other solutes because it had a maximum solubility of approximately 10 wt % at room temperature.

Influence of Temperature on Color of Emulsions. The absolute refractive indices of mineral oil and glucose solutions having concentrations ranging from 0 to 30 wt % were measured as a function of temperature (Table 2). Both the refractive indices of glucose solutions and the refractive index of mineral oil decreased as temperature was raised from 20 to 80 °C. However, the gradient of the decrease of the refractive indices with temperature of both glucose solutions and mineral oil were approximately constant, and the relative refractive index was therefore temperature independent. This explains why the color of emulsions containing sugars did not significantly change when the temperature of the system increased.

CONCLUSIONS

This study has shown that the addition of solutes such as glucose, fructose, lactose, and glycerol can have a pronounced influence on the color of emulsions. The physical basis for color of emulsions is the interaction of light waves with emulsion droplets. Light scattering depends on the optical properties of emulsion droplets and the surrounding media. Adding sugars to the aqueous phase of emulsions lowers the relative refractive index at the oil−water interface influences. As the relative refractive index approaches 1, scattering and absorption are strongly reduced. As a result, spectral reflectance values are lower and emulsions appear less turbid. Adding sugar to emulsions has, therefore, the same effect on the color of emulsions as lowering the oil droplet concentration has. The decrease in refractive index depends on the molecular structure of the solute. The addition of high concentrations of fructose decreases turbidity more significantly than the addition of glucose or glycerol. The color and appearance of emulsions was not influenced by an increase in temperature. Although refractive indices of both the dispersed and the continuous phase are temperature-dependent, the relative refractive index remained constant within the observed temperature range.

Our results have important implications for the food science industry. The addition of optically active components to the aqueous phase of not only emulsions but any aqueous dispersion of particles can be used to alter the color of food products. Adding optically active compounds that are capable of reducing the relative refractive index can be used to mask the presence of oil droplets in emulsions. Adding solutes that increase the relative refractive index at the oil/water interface can be used to increase the turbidity. Optically active food additives could therefore be used to increase the whiteness of skim milk. The application of light scattering theory to food systems containing particles can be used to develop computer models that will help manufacturers reduce costs, ensure product quality, and enhance customer satisfaction.

ACKNOWLEDGMENT

The authors thank Julian McClements for fruitful discussions.

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Received for review March 30, 2000. Revised manuscript received August 2, 2000. Accepted August 2, 2000. This project was supported by the Tennessee Agricultural Experiment Station.

JF000418G