Physical Properties of Liquid Edible Oils

John N. Coupland¹ and D. Julian McClements*

Biopolymers and Colloids Research Laboratory, Department of Food Science, University of Massachusetts, Amherst, Massachusetts 01003

ABSTRACT: Literature values of density, viscosity, adiabatic expansion coefficient, thermal conductivity, specific heat (constant pressure), ultrasonic velocity, and ultrasonic attenuation coefficient are compiled for a range of food oils and water at 20°C, and a series of empirical equations are suggested to calculate the temperature dependency of these parameters. The importance of these data to the application of ultrasonic particle-sizing instruments to food emulsions is discussed. *JAOCS 74*, 1559–1564 (1997).

KEY WORDS: Edible oils, emulsions, physical properties, temperature, ultrasound.

Edible oils extracted from plant and animal sources are important in foods and various other industries (e.g., cosmetics, pharmaceuticals, lubricants). They are key components of the diet and also provide characteristic flavors and textures to foods. During extraction, purification and usage, oils undergo a variety of processing operations, including frying, distillation and chemical modification which may alter their properties. However, prediction of the behavior of oils under real processing conditions from molecular properties is beyond current understanding. Instead, semi-empirical equations are developed that relate the property of interest (e.g., time for fat to drain from a fried potato chip) to independently measurable bulk properties (e.g., density, viscosity, and surface tension). With these equations, it is possible to predict how changes in the properties of an oil alter the efficacy of a process without resorting to time-consuming trial-and-error experiments. The physical properties of edible oils depend primarily on composition (and hence on biological origin) and temperature. In the current work, we have compiled selected bulk parameters for oils in terms of these variables.

Additionally, emulsions that contain edible oils are important in many foods (e.g., milk, salad dressings, ice cream, margarine) (1). In these foods, many of the oil droplets are too small (<1 μ m) to be readily observed by light microscopy and too concentrated (>1%) to be characterized by light scattering. Development of new technologies to characterize food

¹Current address: Department of Food Science, Pennsylvania State University, University Park, PA 16802.

*To whom correspondence should be addressed.

E-mail: mcclements@foodsci.umass.edu.

emulsions would be extremely valuable for product development and quality control. A promising approach to this problem is the use of ultrasound (2-5; McClements, D.J., and J.N. Coupland, submitted for publication). A range of commercial instruments has recently become available to measure ultrasonic velocity and/or attenuation spectra for liquids. These spectra can be converted to droplet size distributions by using ultrasonic scattering theory (2,4). Interpretation of the spectra requires detailed information about the physicochemical properties of the component phases, specifically, ultrasonic velocity (c), attenuation (α), specific heat at constant pressure (Cp), density (ρ) , adiabatic expansion coefficient (B), viscosity (η), and thermal conductivity (τ). At present, the application of ultrasonic particle-sizing technologies to food emulsions is limited because the physicochemical properties of many edible oils are not tabulated. For this reason, we present a compilation of the relevant parameters for a range of common food oils. We start by compiling available measured values at a single temperature (20°C) and then consider various functions that can be used to estimate temperature dependency.

Physical properties of oils at 20° C. The relevant parameters are compiled from a variety of literature sources in Table 1. When available, data cited represent a real measurement at 20° C. Extrapolations are used only when data are available above and below this temperature. Exceptions to this rule are noted in the table. Similar physical parameters are also compiled for water as a comparison. To a first approximation, the aqueous phase of an emulsion can be assumed to be equivalent to pure water, and these data may be helpful in interpreting ultrasonic spectra of an emulsion.

Temperature dependence of food oil properties. The following equations are used to model the temperature dependency of the physical properties of oils:

$$c = c_0 + c_1 T \tag{1}$$

$$\rho = \rho_0 + \rho_1 T \tag{2}$$

$$Cp = Cp_0 + Cp_1 T$$
[3]

$$\eta = \eta_0 \exp[-\eta_1 / k(T + 273.13)]$$
 [4]

where subscripted terms are constants, T is temperature (°C), and k is the Boltzmann constant. These equations have been

TABLE 1 Physical Properties of Liquid Edible Oils at 20°C

	С	$\alpha (Np \cdot m^{-1})$	Ср	ρ	η	В	τ
Oil	$(m \cdot s^{-1})$	(2 MHz)	$(J \cdot kg^{-1} \cdot \circ C^{-1})$	(kg·m ⁻³)	(mPa·s)	$(\times 10^{-4} \cdot {}^{\circ}C^{-1})$	$(W \cdot m^{-1} \cdot {}^{\circ}C^{-1})$
Water ⁶	1482.7 ⁷		4.176	998.2	1.00	2.07	0.604
Sunflower	1471.6 ⁸		2.197 ^{11,c}	919^{16}	47 ⁱ	6.61 ¹⁶	
Corn	1469.5 ⁸		1.956 ^{12,c}	920 ^{17,f}	64.5 ⁱ	$7.22^{17,f}$	
Olive	1464.0^{8}	$6.5^{9,b}$	1.895 ^{11,c}	915.8 ¹⁸	92.0 ⁱ		0.166 ²²
Rape	1468.4 ⁸	$3.6^{9,b}$	1.834 ^{11,c}	911.4 ^{17,f}	73 ^{19,f}	$7.19^{17,f}$	0.160^{23}
Cotton			1.916 ^{13,d}	918.7 ¹⁸	51 ^{18,g}	7.30^{21}	0.172 ^{13,d}
Peanut	1465.9 ⁸	$6.0^{9,b}$		913 ¹⁶	74 ⁱ	6.52^{16}	$0.17^{23,h}$
Palm	1459.3 ^{8,a}		2.000^{14}	919 ¹⁸	85^{14}		
Safflower	1471.4 ⁸	$4.0^{9,b}$		$922.0^{9,b}$		65 ⁱ	
Soy	1469.8 ⁸	4.9^{10}	1.917 ^{15,e}	$922.8^{17,f}$	$59^{19,f}$	7.24 ^{17,f}	

^aExtrapolated from 50°C. Note: Values shown are either reported directly from the literature source cited or extrapolated from adjacent temperatures. Superscripted numbers indicate reference for data. ^bRecorded at 19.4°C.

Recorded at 19.4 C.

^cExtrapolated from 70°C.

^dRecorded at 25°C.

^eRecorded at 19.7°C

^fExtrapolated from 23.9°C. ^gExtrapolated from 37.8°C by using correlation from Reference 22. ^hRecorded at 33°C.

ⁱCoupland, J.N., and D.J. McClements, submitted for publication.

successfully applied to food oils (8,17,18; Coupland, J.N., and D.J. McClements, submitted for publication). The thermal expansion coefficient is by definition: $B = -(\partial \ln \rho / \partial T)_p$ (6); so, its temperature dependency can be calculated from the constants given for the density correlations. Values for the constants in equations 1–4 were calculated from published measurements and are listed in Table 2. Thermal conductivity and ultrasonic absorption coefficient are discussed separately below. Complementary equations for the properties of water are listed in the Appendix section. There is relatively little variation in the properties of different oils; thus, average values from Table 2 are used to calculate the values for a typical food oil for comparison with water in Figure 1.

An alternative series of empirical relationships for oils was developed by Choi and Okos (30), who measured the temperature dependency of thermal conductivity, thermal diffusivity, density, and specific heat for a group of food oils (milk fat, vegetable oil, lard, and corn oil) and developed a series of generic equations for "fat." These equations provide valuable approximations but should be treated with caution because the predictions can deviate substantially from observations published elsewhere.

DISCUSSION

Few materials are as well characterized as water; consequently, the data available (see the Appendix section) are of high quality. On the other hand, food oils often exhibit significant variations in their composition; consequently, it is impossible to define unique values for any oil. None of the data reported here represent a survey of the range of measured parameters for all varieties of a particular oil; so, the degree of interspecies variability remains undefined. An estimate may be obtained by considering the relatively low variation ($\pm 1.5\%$ at 50°C) (31) in reported density for palm oil from



FIG. 1. Temperature dependence of the thermophysical properties of water (w) and an average vegetable oil (o). (A) Ultrasonic velocity *C*, (B) specific heat $C_{p'}$ (C) density ρ , (D) thermal expansion coefficient *B*, (E) viscosity η , and (F) thermal conductivity τ . Data are calculated from Equations 1–8 by using average data from Table 2, data from Table 4, and values given in the text.

TABLE 2						
Empirical Constants to	Predict the	Physical	Properties	of Liquid	Edible	Oils

degrindegr		ρ	ρ_1		η_1	c_0	<i>C</i> ₁	Cp_0	$Cp_1 \cdot 10^3$		Т		
concur97.16-0.70-1.4.912.5.6-1.4.912.5.6-1.4.912.5.60.099Concur16.75-0.71-0.3.312.5.6-1.4.912.5.70.093Concur16.75-0.71-1.3.312.5.6-1.4.912.5.70.0930.998Concur16.75-0.71-1.3.912.5.7-1.3.912.5.70.9390.938Concur16.75-0.71-1.3.912.5.7-1.3.912.5.7-1.3.910.9390.938Concurs-1.3.912.5.7-1.3.91-1.3.1-3.21-1.88.2.7.10.939Concursed-1.3.11.3.1-3.21-1.88.2.7.17.09.991Concursed-1.3.11.3.1-3.2-1.88.4.0.7.07.09.991Concursed-1.3.11.3.1-3.2-1.88.4.0.7.07.09.991Concursed-1.3.11.3.1-3.2-1.88.2.7.107.09.991Concursed-1.3.1-3.1-1.73.559.0919.09.091Concursed-1.3.1-3.1-1.73.559.0919.09.091Concursed-1.3.1-3.11.973.554.109.0919.091Concursed-1.4.33.0.5-1.3.1-3.11.973.556.0919.091Concursed-1.3.1-3.11.973.556.0919.0919.091Concursed-1.3.13.31 <th></th> <th>(kg·m⁻³)</th> <th>$(kg \cdot m^{-3} \cdot \circ C^{-1})$</th> <th>$\ln \eta_0$</th> <th>(kJ·mol^{−1})</th> <th>$(m \cdot s^{-1})$</th> <th>$(m \cdot s^{-1} \cdot \circ C^{-1})$</th> <th>$(J \cdot kg^{-1} \cdot \circ C^{-1})$</th> <th>$(J \cdot kg^{-1} \cdot {}^{\circ}C^{-1})$</th> <th>Reference</th> <th>(°C)</th> <th>п</th> <th>r ²</th>		(kg·m ⁻³)	$(kg \cdot m^{-3} \cdot \circ C^{-1})$	$\ln \eta_0$	(kJ·mol ^{−1})	$(m \cdot s^{-1})$	$(m \cdot s^{-1} \cdot \circ C^{-1})$	$(J \cdot kg^{-1} \cdot \circ C^{-1})$	$(J \cdot kg^{-1} \cdot {}^{\circ}C^{-1})$	Reference	(°C)	п	r ²
Coconut -14.91 29.44 14 12-50 6 0.907 Coconut 1060-75 -0.71 5.00 93.2-11 0 93.2-11 0 93.2-11 0 93.2-11 0 93.2-11 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-1 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 93.0-0 0 0 93.0-0 10.0 133.1-0 -3.2 28.0-10 7 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0 0.99.0 0	Coconut	937.16	-0.70							17	37.8-110	6	1.000
Concourt-13.6325.669938.7-1060.997Concourt0.65-13.6027.181723.9-11070.998Concourt-13.4526.09153.25-3.22820.9000000900Concourt-13.4526.09153.25-3.22820.9000000900900Contonsced-13.65-13.85-3.22820.9000100.00100	Coconut			-14.91	29.44					14	25-50	6	0.999
Coom 100,9,75 -0,71 Cons 100,9,75 -0,65 20,60 7 0,935 Com -13,40 27,18 -13,40 27,18 19 23,90 0,998 Com -13,40 27,18 -2,23 8 20-0 30 0,999 Com -13,40 25,51 8 20-0 30 0,999 Com -13,43 2,55 1,93 2,55 8 20-0 30 0,999 Cottonseed ⁰ -10 -13,10 2,46 18 60,-0 - 0,999 Cottonseed ⁰ -13,01 2,46 -3,24 28 20-0 7 0,999 Crapseed -13,01 2,46 -13,01 2,46 -14 3,32,4 -3,2 28 20-0 7 0,999 Chika -14,33 23,12 -1 7 23,9110 7 0,999 Olike -14,33 3,33 -3,1 3,48 20-0	Coconut			-13.53	25.66					19	38.7-110	6	0.997
Com com94.23 -1.3.60-0.6531.30 -1.3.6027.18-1.3.60 -1.3.6027.18-1.3.60 -1.3.6027.18-0.929 -0.0700.079 -0.070 <td>Coconut</td> <td>1069.75</td> <td>-0.71</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>16</td> <td>20-80</td> <td>7</td> <td>0.955</td>	Coconut	1069.75	-0.71							16	20-80	7	0.955
Com-13.4527.18-13.4526.09990.0980.098Com-13.4526.09-3.23820-0700.999Com-13.4526.19-3.23820-0700.999Cottonseed-15.35-3.241.932.551820-0700Cottonseed-16.10-16.10-16.10-16.101.992.301840-07100Cottonseed-16.7-16.10-16.10-13.17-3.242820-07100999Cottonseed-16.1026.6-12.10-2.301840-0710999Cottonseed-16.1026.6-12.10-2.102820-1729.917999Cottonseed95.52-0.68-13.10-3.232820-1729.917999Olive-14.3529.12-13.13-3.32820-1710999Olive-14.3930.35-14.193.0514-14.9090999Palm-14.2925.9-14.193.0514-14.9090999Palm-14.2925.9-12.693.231690999Palm-14.2925.9-14.19160.999199Palm-14.2925.9-14.1916199199Palm-14.2925.9-14.1916199199Palm-14.	Corn	934.23	-0.65							17	23.9–110	7	0.998
Com	Corn			-13.80	27.18					d	5–90	90	0.998
ComCon1532.4-3.23-3.23-3.242.820-703090Cottonsced1533.5-3.21.932.551.81.5-6011.501.00Cottonsced1.932.301.84.0-7079.993.001.84.0-7079.99Cottonsced92.30-0.671.539-3.2480.0-7079.99Crapsced1.551.6473.231.770.99Crapsced1.55-3.21.71.72.3-11079.99Milkored95.50-0.671.30124.66-3.21.72.53.7.0099.99Ohre-13.0124.661.511-3.11.72.53.7.0099.99Ohre-14.3529.12-1.3.1-3.31.82.0-71.99.99Ohre-14.4829.00-3.231.44.0-5070.99Palm olein-14.8930.35-1.21.60.409.999.99Palm olein-14.8930.3552.8.9-3.231.60.909.99Palm olein-14.8924.551.29-3.241.84.2-771.09.99Palm olein-14.893.0.352.8.9-3.231.60.909.999.999.999.999.999.999.999.999.999.999.999.999.999.999.99 </td <td>Corn</td> <td></td> <td></td> <td>-13.45</td> <td>26.09</td> <td></td> <td></td> <td></td> <td></td> <td>19</td> <td>23.9–110</td> <td>7</td> <td>0.979</td>	Corn			-13.45	26.09					19	23.9–110	7	0.979
Contonsced1533.5-3.21.9.32.58.42.02.0Cottonsced1.8.64.184.181.8.64.181.8.64.181.8.63.2.43.23.23.2.4	Corn					1532.4	-3.23			8	20-70	36	0.999
Catonseed1.9.32.5.51.81.5.4<	Corn					1533.5	-3.2			28	20		
Cathonseed1.864.181.32.5531.00Cathonseed1.924.0618640-7070.999Carpesed1.924.0618640-7070.999Carpesed1.53.4,7-3.21.82.070.991Carpesed-153.4,7-3.2172.9.11070.991Milkiked95.5.9-0.67-1.53.4,7-3.2172.9.11070.991Milkiked93.5.2-0.6-1.53.4,7-3.2182.0.20.991Olive0.43.52.1.2-1.82.0.73.60.991Olive1.53.1,7-3.32.82.00.999Palm1.53.4,7-3.382.0-73.60.999Olive1.53.4,7-3.382.0-73.60.999Palm1.53.4,7-3.382.0-73.60.999Palm1.53.4,7-3.282.0-73.60.999Palm1.4.22.6.9-1.680.700.909Palm1.4.22.6.9-1.680.700.909Palm1.2.62.6.9-1.60.9990.999Palm1.2.62.6.91.90.999Palm-	Cottonseed ^a							1.93	2.55	18	15-60		
Catonscede ¹ 1.9.22.3.01.84.0.24.0.61.0.24.0.61.0.24.0.60.909Crappesed-153.4,7-3.22.820.770.909Crappesed13.012.4.6-2.820.770.909Milk Aat-13.012.4.6-1.72.3.9.1070.909Milk Aat-13.012.4.6-1.72.3.9.1070.909Olive1.8.12-1.82.0.700.908Olive1.8.12-1.82.0.700.908Olive1.8.12-1.82.0.700.909Palm1.52.9-3.23-82.0.71.9Palm1.9.73.051.41.9000.9080.998Palm1.9.73.051.40.9090.998Palm1.52.9-3.231.01.00.908Palm Alein-1.2.92.8.93.2.31.01.00.908Palm Alein-1.2.92.8.9-3.231.01.00.908Palm Alein-1.2.92.8.9-3.231.01.00.908Palm Alein-1.2.92.8.9-3.231.01.00.908Palm Alein-1.2.92.9.91.2.91.01.01.0 </td <td>Cottonseed</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>1.86</td> <td>4.18</td> <td>13</td> <td>25-45</td> <td>3</td> <td>1.000</td>	Cottonseed							1.86	4.18	13	25-45	3	1.000
CotonsedV1.924.061.86.06.7V999Grapseed923.00-0.671533.9-1.24820V999Grapseed955.69-0.671534.7-3.2227999Mik At-0.671534.7-3.21723.9-11070.999Mik Newed935.52-0.68-0.671723.9-11070.999Olive-0.81528.9-3.238820.7000.999Olive-0.81528.9-3.238820.7000.999Palm-14.4329.50-158.9-3.2314000.999Palm-14.4329.50-14.9330.5114000.999Palm kernel-14.4329.50-11.973.0514000.999Palm kernel-14.4329.50-12.99-3.231420.7070.999Palm kernel-14.2028.59-3.231620.70160.999Panut-14.2024.55152.9-3.231620.7070.909Panut-14.2024.65152.9-3.241620.7070.909Panut-14.2024.65152.9-3.241620.7070.909Panut-14.2024.65152.9133.4-3.24160.9099Panut-14.20	Cottonseed ^b							1.99	2.30	18	40-70		
Cambe Grappesed93.00-0.67-1.33-3.2-820.70699Grappesed-55.69-0.67-13.0124.66-1.2-1.223.9-11070.99Milkowed Milkowed935.52-0.68-1.4.3529.12-1.4.323.9-11070.99Olive1.4.3529.12820.7080.998Olive152.69-3.23-820.701099Palm152.69-3.23820.701099Palm14.9330.35-1430.5070.996Palm olein14.9330.35-100.20.6040.999Pantu12.6230.35-100.20.6040.999Peanut12.6230.35-100.20.6040.999Peanut12.6212.89-3.23820.771000Peanut12.6212.89-3.23101020.6040.999Peanut12.6212.89-3.232.06102.99.11070.906Peanut12.6212.89-3.232.06102.99.11070.906Peanut12.6212.8913.81-3.232.0610 <td>Cottonseed^c</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>1.92</td> <td>4.06</td> <td>18</td> <td>60-80</td> <td></td> <td></td>	Cottonseed ^c							1.92	4.06	18	60-80		
Grappesed1533.9-3.24.891-07.0360.999Grappesed-57.0-0.68-37.03.05-37.00.999Milkated935.5-0.68-25.037.700.999Olive-0.68-37.0152.9-3.23-820.700.099Olive-14.3529.12-3.23-820.700.099Olive-14.3529.13-3.23-850.700.099Palm-14.3529.00-3.1-850.700.099Palm-14.4829.00-3.1-850.700.099Palm lori-14.4829.00-14.933.05-1430.050.099Palm lori-14.2228.59-1430.0514-0.000.099Panul-14.2228.59-1430.051430.050.999Panul-14.2228.59-12.831830.700.099Panul-14.2228.59-12.831830.751430.97Panul-14.2228.59-12.831830.9719.99Panul-14.2228.59-12.831830.9719.99Panul-14.23-16.671820.703019.99Panul-14.23-16.8320.701820.7019.99Panul-14.33152.9-12.8420.701820.7019.99Panul-13.62152.919.92 <t< td=""><td>Crambe</td><td>923.00</td><td>-0.67</td><td></td><td></td><td></td><td></td><td></td><td></td><td>17</td><td>23.9–110</td><td>7</td><td>0.999</td></t<>	Crambe	923.00	-0.67							17	23.9–110	7	0.999
GraphesedIsal.?-1.2282020Isequerella95.69-0.67-1.3.0124.69I2537.7090.991Milkwed935.52-0.68-1723.9-11070.999Olive1.4.3529.12-1723.9-11070.999Olive1.4.3529.12-820.70300.999Olive152.9-3.3850.70199.991Palm1.4.8329.60-1.973.051420.5070.996Palm Olein1.4.8330.35-1020.6070.996Peanut1.4.2928.59-1020.6070.996Peanut1.4.2928.59-1020.6070.996Peanut1.52.9-3.2110120.60160.999Peanut1.52.9-3.2110120.60160.999Peanut1.52.9-3.2110120.6011020.601100.990Peanut1.52.9-3.231011020.601100.901010.90110.9010.9010.9010.9010.9010.9010.9010.9010.9010.90 <td>Grapeseed</td> <td></td> <td></td> <td></td> <td></td> <td>1533.9</td> <td>-3.24</td> <td></td> <td></td> <td>8</td> <td>20-70</td> <td>36</td> <td>0.999</td>	Grapeseed					1533.9	-3.24			8	20-70	36	0.999
Lesquerella955.69-0.67-0.67-0.999Milk at-13.0124.66-152.89-3.23370.999Olive14.3529.12-45.090.999Olive152.89-3.23282.0Palm153.1-3.3282.00.999Palm1.51-3.3282.00.999Palm1.52-1.573.05140.999Palm loin1.589.011.901.900.9990.9920.9990.9920.991<	Grapeseed					1534.7	-3.2			28	20		
Milk rdi -0.60 -13.01 24.66 25 37-70 90 901.00 0.999 Olive -14.35 29.12 -0.68 20.99 0.999 Olive 152.9 -3.23 8 20.70 36 0.999 Olive 1515 -3.1 8 20.70 30 0.999 Palm -14.88 29.00 1.97 3.05 4 0.999 Palm kernel -14.88 29.60 1.97 3.05 14 30-50 7 0.996 Palm kernel -14.23 28.59 -1.42 28.59 -1.42 28.90 0 0.999 Peanut -14.22 28.59 -3.2 8 20-70 36 0.999 Peanut -14.22 28.59 -3.2 8 20-70 36 0.999 Peanut -14.22 28.59 -3.2 8 20-70 36 0.999 Peanut -14.20 24.66 -1.97 4.89 2.3-510 7 0.996 Peanut -12.92	Lesquerella	955.69	-0.67							17	23.9–110	7	0.999
Milkwed 935.52 -0.68	Milk fat			-13.01	24.66					25	37-70	9	0.991
Olive-14.3529.1200.999OliveIS31-3.328Q-70100.999PalmIS31-3.328Q-70100.999Palm-14.8829.00IS31430.5550.999Palm loline-14.8829.00IS1430.5670.996Peanut-14.2228.59IS1020-6040.999Peanut-14.2228.59-3.2328209Peanut-14.2228.59-3.2328209Peanut127.73-0.60IS2.99-3.2328209Peanut927.13-0.60IS2.99-3.23282090.991Peanut92.713-0.60IS2.99-3.2328201010000.991Peanut92.753-0.66IS2.99-3.241.671827-751.001.000.993Rape93.05IS3.4-3.22.661.671827-751.000.99390.993Rape-13.1624.60IS3.4-3.2282000.99390.993	Milkweed	935.52	-0.68							17	23.9–110	7	0.999
Oive152.8-3.3820-70303090Palm151-3.1850-7000909Palm-14.8829.001440-5050099Palm kei-14.8829.001440-5070099Palm kei-14.9330.35-1440-5070099Peanut-14.9330.35-128.9-1440-5070099Peanut-12.6924.55-128.9-3.23820-70360.999Peanut-12.69152.9-3.228201827-5770Peanut927.13-0.60-152.9-3.22.061.671827-5770.00Peanut92.13-0.602.061.671827-5770.00Rape92.05-0.66-1.922.06161827-5770.90Rape93.42-0.60-153.4-3.24820-70360.99Rape91.42-0.60-153.4-3.24820-70360.99Safflower153.4-3.24820-70360.99Safflower153.4-3.24820-70360.99Safflower133.6-3.24820-70 <t< td=""><td>Olive</td><td></td><td></td><td>-14.35</td><td>29.12</td><td></td><td></td><td></td><td></td><td>d</td><td>5-90</td><td>90</td><td>0.998</td></t<>	Olive			-14.35	29.12					d	5-90	90	0.998
Olive153-3.32820Palm1515-3.1850-7000.99Palm kerrel-14.8829.011.973.051.4Palm kerrel-14.8829.011.973.051.40.500.99Peanut-14.2228.591.921.921.920.990Peanut-14.2228.59-1.231.00.990Peanut-14.2328.59-3.231.0820-703.0Peanut-12.6923.51-3.21.827.571.92Peanut-12.6923.61-3.21.827.571.92Peanut-12.6926.61.671.827.571.92Peanut-13.6626.61.971.823.9-11071.00Rape92.305-0.66-2.061.671.827.571.99Rape-13.1624.60-1.974.891.847.771.90Rape-13.5726.68-1.62.99.999.99Rape-13.602.60-2.80.999.99Rape-13.602.60-2.80.999.99Safflower-1.35.4-3.282.0-09.99Safflower-1.933.61-2.45.5569.99Safflower-1.93.6-3.2-1.60.909.99Safflo	Olive					1528.9	-3.23			8	20-70	36	0.999
Palm1515-3.1.85.70100.999Palm kernel-14.8829.601.973.0514.5050.999Palm kernel-14.9330.351.973.0514.20-5070.999Peanut-14.9330.351.020-60.0990.999Peanut-12.6924.551020-60.0.099Peanut-12.6925.89-3.23820-70.0.0Peanut927.13-0.60152.99-3.23160.80 <td>Olive</td> <td></td> <td></td> <td></td> <td></td> <td>1531</td> <td>-3.3</td> <td></td> <td></td> <td>28</td> <td>20</td> <td></td> <td></td>	Olive					1531	-3.3			28	20		
PalmPalm1.973.0514Palm lole-14.8829.601430.5050.999Palm ole-14.2228.591002.6600.999Peanut-14.2228.591002.6600.999Peanut-14.2228.59-3.23820.70360.999Peanut-14.230.60152.9.9-3.23820.70360.999Peanut-14.2420.50-1.261.671827.571070.966Peanut-1.3.662.6.61.974.891847.771.000Peanut-1.3.262.6.61.974.891847.771.000Rape-13.1624.60-1.974.891847.771.000Rape-13.1624.60-1.022625.100250.998Rape-13.1624.60-1.02280.99928.91070.906Rape-1.1.624.60-1.02280.99928.91070.906Rape-1.1.624.60-1.2.4-3.24820.70360.999Rape-1.1.6021.80-1.99-1.4-3.24820.70360.999Safflower-1.1.6021.80-1.99-1.6-1.99245.5560.998Safflower-1.1.6021.80-1.3.63-3.4-3.22820.70360.99	Palm					1515	-3.1			8	50-70	10	0.999
Palm kernel-14.8829.60	Palm							1.97	3.05	14			
Palm olein -14,93 30.35	Palm kernel			-14.88	29.60					14	30–50	5	0.999
Peanut -14.22 28.59 -14.22 28.59 -14.22 28.59 -14.22 28.59 -12.69 24.55 10 20-60 4 0.999 Peanut -12.69 24.55 1528.9 -3.2 28 20 - - - 0 0.999 Peanut -12.69 1529.9 -3.2 28 20 - - 0 0.999 Peanut - -0.60 - 2.06 1.67 18 27-77 - - Peanut - - 2.06 1.67 4.89 18 47-77 - 0.996 Peanut - - - 2.2.6 1.97 4.89 18 47-77 1.00 Rape - - 1.3.6 26.26 - 1.97 4.89 18 47-77 0.996 Rape - - 1.53 - - 1.97 4.89 18 40-70 3.6 0.999 Rape - - - 1.92 2.9.5 1.0 0.990 0.999 Rape - - 1.53 - - 1.6 0.40 0.991 <t< td=""><td>Palm olein</td><td></td><td></td><td>-14.93</td><td>30.35</td><td></td><td></td><td></td><td></td><td>14</td><td>20-50</td><td>7</td><td>0.996</td></t<>	Palm olein			-14.93	30.35					14	20-50	7	0.996
	Peanut			-14.22	28.59					d	5-90	90	0.999
Peanut 1528.9 -3.23 8 20-70 36 0.99 Peanut 927.13 -0.60 1.67 18 27-75 9 99 Peanut 2.06 1.67 18 27-75 1.000 Rape 923.05 -0.66 1.97 4.89 18 47-77 7 1.000 Rape 923.05 -0.66 19 23.9-110 7 0.906 Rape -13.16 24.60 10 20-60 5 0.998 Rape -13.16 24.60 26 20 0 099 Rape -13.16 24.60 26 20 0 099 Rape -13.57 26.68 20 0 099 Rape -13.61 24.60 20 0 099 Rape -13.63 24.60 16 0-80 9 0.992 Safflower -13.53 1534.4 -3.24 8 20-70 36 0.000 Safflower -14.80 29.50 1535.4 -3.24 8 20-70 36 0.992 Safflower -14.80 29.50 6 .982 0 0 0.992	Peanut			-12.69	24.55					10	20-60	4	0.999
Peanut1529.9 -3.2 28 20 Peanut -0.60 -0.61 $0-80$ 9 9 Peanutb 2.06 1.67 18 $27-57$ 7 Peanutb 2.30 -0.66 1.97 4.89 18 $47-77$ 7 Rape 923.03 -0.66 26.26 1.97 $23.9-110$ 7 0.998 Rape -13.26 24.60 10 $20-60$ 5 0.998 Rape -13.57 24.60 24.60 26 25 00 0.999 Rape -13.57 26.68 d 5 0.998 Rape -13.57 26.68 d 5 0.999 Rape -13.63 25.00 d 48 $20-70$ 36 0.999 Rape -13.63 25.00 d -3.24 8 $20-70$ 36 0.999 Rape -14.80 29.50 d -3.24 8 $20-70$ 36 0.999 Safflower -14.80 29.50 d -3.24 d $5-55$ 6 0.988 Safflower -14.80 29.50 d -3.29 d 24 $5-55$ 6 0.999 Safflower -14.80 26.46 d -3.29 d $5-55$ 6 0.999 Safflower -14.80 26.46 d 1.87 3.0 15 0.999 Soy -14.80 26.46 -3.29 d $5-55$ 6 <td>Peanut</td> <td></td> <td></td> <td></td> <td></td> <td>1528.9</td> <td>-3.23</td> <td></td> <td></td> <td>8</td> <td>20-70</td> <td>36</td> <td>0.999</td>	Peanut					1528.9	-3.23			8	20-70	36	0.999
Peanut 927.13 -0.60 -0.60 9 0.991 Peanut -13.06 2.06 1.67 18 27-57 7 Rape 923.05 -0.66 -13.26 26.26 1.97 4.89 18 47-77 Rape -13.26 26.26 1.97 4.89 18 47-77 7 0.906 Rape -13.26 26.62 10 2.06-10 5 0.998 Rape -13.16 24.60 2.6 2.5 0 0 0 Rape -13.16 24.60 -3.24 8 20-70 36 0.999 Rape -3.13.16 24.60 -3.24 8 20-70 36 0.999 Rape -3.13.7 26.68 -3.24 8 20-70 36 0.999 Safflower -14.80 29.50 -3.24 8 20-70 36 0.999 Safflower -14.80 29.50 -3.24 8 20-70 36 0.999 Safflower -14.70 21.80 -3.24 8 20-7 36 0.999 Safflower -14.80 29.50 -3.29 24 5-55 6 0	Peanut					1529.9	-3.2			28	20		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Peanut	927.13	-0.60							16	0-80	9	0.991
Peanut ^a 1.97 4.89 18 47-77 Rape 923.05 -0.66 17 23.9-110 7 1.000 Rape -13.26 26.26 19 23.9-110 7 0.996 Rape -12.92 24.85 10 20-60 5 0.998 Rape -13.16 24.60 26 26 25 0.986 Rape -13.57 26.68 26 26 26 0.999 Rape -13.57 26.68 20 28 20-70 36 0.999 Rape -14.80 29.50 1533.4 -3.24 8 20-70 36 0.099 Safflower -14.80 29.50 10 20-60 5 0.918 Safflower -14.80 29.50 1535.4 -3.24 8 20-70 36 0.000 Safflower -11.76 21.80 1535.4 -3.24 8 20-70 36 0.998 Safflower -14.80 29.50 1535.4 -3.24 24 5-55 6 0.973 Safflower -14.70 24.0 15.5 9 0.944 5-50 9 0.944	Peanut							2.06	1.67	18	27–57		
Rape 923.05 -0.66 17 23.9-110 7 0.096 Rape -13.26 26.26 19 23.9-110 7 0.996 Rape -12.92 24.85 26 26 26 26 0.998 Rape -13.57 26.68 26 26 0.999 0.999 Rape -13.57 26.68 28 20 0.999 Rape 153.4 -3.24 8 20-70 36 0.999 Safflower 153.4 -3.24 8 20-70 36 0.909 Safflower -14.80 29.50 1534.4 -3.24 8 20-70 36 0.909 Safflower -11.76 21.80 10 20-60 5 0.991 Safflower -11.76 21.80 10 20-60 5 0.993 Seal 930.38 -0.64 -16.57 34.70 24 15-55 9 0.84 Seal -16.57 34.70 -3.29 8 5-70 9 0.997	Peanut ^{<i>b</i>}							1.97	4.89	18	47–77		
Rape -13.26 26.26 19 23.9-110 7 0.996 Rape -12.92 24.85 10 20-60 5 0.998 Rape -13.16 24.60 26 25 0.86 Rape -13.57 26.68 d 5-90 90 0.999 Rape -13.77 26.68 d 0-80 9 0.999 Rape 153.9 -3.24 8 20-70 36 0.999 Safflower -0.60 1534.4 -3.24 8 20-70 36 0.992 Safflower -14.80 29.50 d 5-90 90 0.998 Safflower -14.80 29.50 d 5-90 90 0.998 Safflower 1535.4 -3.2 28 20 20 24 5-55 6 0.988 Safflower 1533.16 -3.09 24 5-55 6 0.984 Seal -16.57 34.70 15 10 0 90 0.997 Soy <td< td=""><td>Rape</td><td>923.05</td><td>-0.66</td><td></td><td></td><td></td><td></td><td></td><td></td><td>17</td><td>23.9–110</td><td>7</td><td>1.000</td></td<>	Rape	923.05	-0.66							17	23.9–110	7	1.000
Rape -12.92 24.85 10 20-60 5 0.998 Rape -13.16 24.60 26 2.5-100 25 0.996 Rape -13.57 26.68 d 5-90 00 0.999 Rape 1532.9 -3.24 8 20-70 36 0.999 Rape 1533.4 -3.2 28 20 70 90 0.992 Safflower -0.60 1534.4 -3.24 8 20-70 36 0.909 Safflower -14.80 29.50 d 5-90 90 0.992 Safflower -14.80 29.50 d 5-90 90 0.998 Safflower -14.80 29.50 28 20 28 20 28 Safflower -14.80 29.50 -3.2 28 20 28 28 29 393 39 0.64 59 0.90 393 39 393 39 34.70 28 20 28 20 28 29 39 39 39<	Rape			-13.26	26.26					19	23.9–110	7	0.996
Rape -13.16 24.60 26 2.5-100 25 0.986 Rape -13.57 26.68 d 5-90 90 0.999 Rape 1532.9 -3.24 8 20-70 36 0.992 Rape 1533.4 -3.2 28 20 <t< td=""><td>Rape</td><td></td><td></td><td>-12.92</td><td>24.85</td><td></td><td></td><td></td><td></td><td>10</td><td>20-60</td><td>5</td><td>0.998</td></t<>	Rape			-12.92	24.85					10	20-60	5	0.998
Rape -13.57 26.68 5-90 90 0.999 Rape 1532.9 -3.24 8 20-70 36 0.999 Rape 1533.4 -3.2 28 20 0.992 Safflower -14.80 29.50 d 0-80 9 0.992 Safflower -14.80 29.50 d 5-90 90 0.998 Safflower -14.80 29.50 d 5-50 6 0.991 Safflower -14.80 29.50 d 5-55 6 0.991 Safflower -14.657 34.70 -3.2 28 20 5 56 0.988 Seal -16.57 34.70 -3.2 24 5-55 6 0.984 Seal -16.57 34.70 -3.2 24 5-55 9 0.844 Soy 934.41 -0.67 -1.26 -3.29 8 5-70 30 0.999 Soy -13.63 26.46 -1.87 3.0 15 1.100 8 0.990	Rape			-13.16	24.60					26	2.5–100	25	0.986
Rape1532.9 -3.24 8 $20-70$ 36 0.999 Rape1533.4 -3.2 28 20 7	Rape			-13.57	26.68					u	5–90	90	0.999
Rape1533.4 -3.2 2820Rice bran931.42 -0.60 16 $0-80$ 9 0.992 Safflower -14.80 29.50 d $5-90$ 90 0.998 Safflower -11.76 21.80 0.991 d $5-90$ 90 0.998 Safflower -11.76 21.80 0.991 d $5-90$ 90 0.998 Safflower -11.76 21.80 0.991 d $5-55$ 6 0.973 Seal 930.38 -0.64 -3.09 24 $5-55$ 6 0.988 Seal -16.57 34.70 24 $5-55$ 6 0.988 Seal -16.57 34.70 24 $5-55$ 6 0.998 Seame -14.10 28.16 d $5-90$ 900 0.997 Soy 934.41 -0.67 1536.2 -3.29 8 $5-70$ 30 0.999 Soy -14.10 28.16 1.87 3.0 15 $1-100$ 8 0.990 Soy -12.96 24.64 $2-55$ 6 0.987 Soybean -13.63 26.46 1.87 3.0 15 $1-100$ 8 0.997 Sperm whale 84.53 -0.65 -3.59 24 $5-55$ 6 0.987 Sperm whale -14.40 27.62 24 $5-55$ 6 0.997 Sperm whale 84.53 -0.65 -15.86 -3.28 8 $5-70$	Rape					1532.9	-3.24			8	20–70	36	0.999
Rice bran931.42-0.601534.4-3.24160-8090.992Safflower -14.80 29.50d5-90900.998Safflower -11.76 21.801020-6050.991Safflower -11.76 21.801020-6050.991Safflower -16.57 34.70245-5560.973Seal -16.57 34.70245-5560.998Seal -16.57 34.70245-5560.998Seame -14.10 28.16 d 5-90900.997Soy934.41 -0.67 1536.2 -3.29 85-70300.999Soy -13.63 26.461.873.0151-10080.990Soybean -13.63 26.461.873.0151-10080.990Soybean -12.96 24.641923.9-11070.997Sperm whale -14.40 27.62245-5560.987Sperm whale -14.40 27.62245-5560.965Sperm whale -14.40 27.62245-5560.999Sunflower -13.83 27.17d5-55900.999	Rape					1533.4	-3.2			28	20		
Sattlower1534.4 -3.24 8 $20-70$ 361.000Safflower -14.80 29.50 d $5-90$ 900.998Safflower -11.76 21.8010 $20-60$ 50.991Safflower1535.4 -3.2 282020Seal930.38 -0.64 24 $5-55$ 60.973Seal -16.57 34.7024 $5-55$ 60.988Seal -16.57 34.7024 $5-55$ 90.984Sesame -14.10 28.16 d $5-90$ 900.997Soy934.41 -0.67 1536.2 -3.29 8 $5-70$ 300.999Soy 1536.2 -3.29 8 $5-70$ 300.999Soy -13.63 26.46 1.87 3.015 $1-100$ 80.990Soybean -12.96 24.64 1.87 3.015 $1-100$ 80.997Sperm whale 884.53 -0.65 1528.5 -3.59 24 $5-55$ 60.987Sperm whale -14.40 27.62 24 $5-55$ 60.967Sperm whale -14.40 27.62 24 $5-55$ 60.997Sunflower -13.83 27.17 d $5-50$ 900.999	Rice bran	931.42	-0.60							16	0-80	9	0.992
Sattlower -14.80 29.50	Safflower			4 4 9 9		1534.4	-3.24			8	20-70	36	1.000
Sattlower -11./6 21.80 10 20-60 5 0.991 Safflower 1535.4 -3.2 28 20 24 5-55 6 0.973 Seal 930.38 -0.64 1533.16 -3.09 24 5-55 6 0.988 Seal -16.57 34.70 24 5-55 6 0.997 Sesame -14.10 28.16 d 5-90 90 0.997 Soy 934.41 -0.67 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20 20 0.999 0.999 Soy 1537.8 -3.4 28 20 20 0.999 0.999 Soy 1537.8 -3.4 28 20 20 0.999 0.99	Safflower			-14.80	29.50					10	5-90	90	0.998
Sattlower 1535.4 -3.2 28 20 Seal 930.38 -0.64 24 5-55 6 0.973 Seal 1533.16 -3.09 24 5-55 6 0.988 Seal -16.57 34.70 24 15-55 9 0.984 Sesame -14.10 28.16 d 5-90 90 0.997 Soy 934.41 -0.67 1536.2 -3.29 8 5-70 30 0.999 Soy 934.41 -0.67 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20 </td <td>Safflower</td> <td></td> <td></td> <td>-11./6</td> <td>21.80</td> <td>4 = 2 = 4</td> <td></td> <td></td> <td></td> <td>10</td> <td>20-60</td> <td>5</td> <td>0.991</td>	Safflower			-11./6	21.80	4 = 2 = 4				10	20-60	5	0.991
Seal 930.38 -0.64 24 5-55 6 0.973 Seal 1533.16 -3.09 24 5-55 6 0.988 Seal -16.57 34.70 24 15-55 9 0.984 Sesame -14.10 28.16 d 5-90 90 0.997 Soy 934.41 -0.67 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20	Safflower	020.20	0.64			1535.4	-3.2			28	20	~	0.070
Seal -16.57 34.70 24 5-55 6 0.988 Seal -16.57 34.70 24 15-55 9 0.984 Sesame -14.10 28.16 d 5-90 90 0.997 Soy 934.41 -0.67 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20 <td< td=""><td>Seal</td><td>930.38</td><td>-0.64</td><td></td><td></td><td>1522.16</td><td>2.00</td><td></td><td></td><td>24</td><td>5-55</td><td>6</td><td>0.973</td></td<>	Seal	930.38	-0.64			1522.16	2.00			24	5-55	6	0.973
Seal -16.57 34.70 24 $15-55$ 9 0.984 Sesame -14.10 28.16 d $5-90$ 90 0.997 Soy 934.41 -0.67 17 $23.9-110$ 7 1.000 Soy 1536.2 -3.29 8 $5-70$ 30 0.999 Soy 1537.8 -3.4 28 20 -100 8 0.990 Soy -13.63 26.46 1.87 3.0 15 $1-100$ 8 0.990 Soybean -12.96 24.64 19 $23.9-110$ 7 0.997 Sperm whale 884.53 -0.65 1528.5 -3.59 24 $5-55$ 6 0.987 Sperm whale -14.40 27.62 24 $5-55$ 9 0.987 Sunflower -13.83 27.17 d $25-50$ 90 0.998	Seal			16 57	24.70	1533.16	-3.09			24	5-55	6	0.988
Sesame -14.10 28.16 5-90 90 0.997 Soy 934.41 -0.67 17 23.9-110 7 1.000 Soy 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20 20 20 20 Soy -13.63 26.46 1.87 3.0 15 1-100 8 0.990 Soybean -12.96 24.64 19 23.9-110 7 0.997 Sperm whale 884.53 -0.65 24 5-55 6 0.987 Sperm whale -14.40 27.62 24 5-55 9 0.987 Sunflower -13.83 27.17 4 25-50 90 0.999	Seal			-16.5/	34.70					24 d	15-55	9	0.984
Soy 934.41 -0.67 17 23.9-110 7 1.000 Soy 1536.2 -3.29 8 5-70 30 0.999 Soy 1537.8 -3.4 28 20 <t< td=""><td>Sesame</td><td>024.41</td><td>0.67</td><td>-14.10</td><td>28.16</td><td></td><td></td><td></td><td></td><td>17</td><td>5-90</td><td>90</td><td>0.997</td></t<>	Sesame	024.41	0.67	-14.10	28.16					17	5-90	90	0.997
Soy 1536.2 -3.29 6 5-70 30 0.999 Soy 1537.8 -3.4 28 20 20 Soy 1.87 3.0 15 1-100 8 0.990 Soybean -13.63 26.46 14 20-50 7 0.997 Sperm whale 884.53 -0.65 24 5-55 6 0.987 Sperm whale -14.40 27.62 24 5-55 6 0.967 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 4 25-50 90 0.998	Soy	934.41	-0.67			1526.2	2.20			17	23.9-110	20	1.000
Soy -3.4 20 20 Soy 1.357.6 -3.4 20 20 Soy 1.87 3.0 15 1-100 8 0.990 Soybean -12.96 24.64 14 20-50 7 0.997 Sperm whale 884.53 -0.65 24 5-55 6 0.987 Sperm whale -14.40 27.62 24 5-55 6 0.967 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 d 25-50 90 0.998	Soy					1536.2	-3.29			8	5-/0	30	0.999
Soy -13.63 26.46 14 20-50 7 0.999 Soybean -12.96 24.64 19 23.9-110 7 0.997 Sperm whale 884.53 -0.65 24 5-55 6 0.987 Sperm whale 1528.5 -3.59 24 5-55 6 0.967 Sperm whale -14.40 27.62 24 15-55 9 0.987 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 d 25-50 90 0.988	SOY					1557.0	-5.4	1 07	2.0	20 15	20	0	0.000
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Soybean 19 23.9–110 7 0.997 Sperm whale 884.53 -0.65 24 5–55 6 0.987 Sperm whale 1528.5 -3.59 24 5–55 6 0.965 Sperm whale -14.40 27.62 24 15–55 9 0.997 Sunflower 1538 -3.28 8 5–70 30 0.999 Sunflower -13.83 27.17 d 25–50 90 0.988	Soubcan			-12.02	20.40 2161					14	20-30 22.0 110	7	0.999
Sperm whate 1528.5 -3.59 24 5-55 6 0.967 Sperm whate -14.40 27.62 24 5-55 6 0.967 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 d 25-50 90 0.988	Sporm what	881 52	_0.65	12.90	24.04					19 24	5 55	6	0.997
Sperm whale -14.40 27.62 24 5-55 6 0.965 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 d 25-50 90 0.988	Sperm what	. 004.00	-0.05			1528 5	_3 50			∠+ 24	5 55	6	0.307
Spenn white 17.40 27.02 24 15-55 9 0.907 Sunflower 1538 -3.28 8 5-70 30 0.999 Sunflower -13.83 27.17 d 25-50 90 0.988	Sperm what	- 1		-14 40	27.62	1920.9	-3.39			24 24	15-55	G G	0.903
Sunflower -13.83 27.17 d 25–50 90 0.999	Sunflower			1-1-10	27.02	1538	_3.28			27	5_70	30	0.907
	Sunflower			-13.83	27.17		5.20			ď	25-50	90	0.998

(continued on next page)

TABLE 2 (continued)

	ρ_0	ρ_1	ln n	η_1	$c_0^{(m,c^{-1})}$	C_1	Cp_0	$Cp_1 \cdot 10^3$	Poforonco	T (°C)		, 2
	(kg·m)	(kg·m··C)	$\Pi \Pi_0$	(кј•шог)	(11.5)	(III's · C)	()·kg · C)	1.Kg . C)	Reference	(C)	11	I
Sunflower			-22.89	43.74					27	25-50	6	0.998
Sunflower					1537.6	-3.3			28	20		
Sunflower	933.76	-0.61							16	20-80	11	0.995
Sunflower ^b			-22.79	42.23					27	25-50	6	0.999
Vegetable					1537.0	-3.4			28	20		
Average												
values	940.00	-0.65	-14.60	28.48	1532.18	-3.25	1.90	5.9				

^aThe relevant equations (1-4) are described in the text. Partially hydrogenated.

^bHydrogenated.

^cHighly hydrogenated.

^dCoupland, J.N., and D.J. McClements, submitted for publication.

various geographical sources. In the absence of more detailed information, it is reasonable to use this level of accuracy for all data reported here.

A sample of oil may undergo various physical and chemical changes during storage, such as crystallization and oxidation. Crystallization becomes thermodynamically favorable when an oil is cooled below its melting point. Nevertheless, crystallization will only occur once stable nuclei are formed in the liquid oil. In bulk oils, only a small degree of supercooling is required to form stable nuclei because of the presence of impurities. In emulsified oils, a much greater degree of supercooling is required (typically 10-15°C) before crystallization is observed because the probability of finding an impurity in an emulsion droplet is extremely small. Therefore, crystallization relies on homogeneous nucleation (32). There are relatively few data compiled for solid fats, and this data compilation is confined to liquid oils. However, at low temperatures, these data should be treated with caution because a small proportion of solid fat will cause significant changes in the physical properties of the oil.

Most food oils contain components that are capable of reacting with oxygen. The most important are the reactions of polyunsaturated fatty acids, which oxidize to form a rancid odor. It is possible to correlate bulk properties of oils with some measurements of oxidation [for example, the specific heat and density of palm oil decrease with degree of unsaturation (14)]. Only a small proportion of an oil needs to be oxidized before a food becomes organoleptically unacceptable. On the other hand, fairly large alterations in composition are required to cause significant changes in most bulk properties. So, it seems reasonable to neglect the effects of oxidation on the physical properties of edible oils (surface tension is a probable exception to this rule). The oxidation behavior of emulsified oils is frequently different to similar oils in bulk (33).

Ultrasonic properties. At relatively low ultrasonic frequencies (f < 10 MHz), most fully liquid oils behave as isotropic fluids, and their velocities are frequency-independent. The oils listed in the present work are all assumed to behave in this manner. Empirical relations are available to predict the ultrasonic velocity of oils from their fatty acid composition (8). Deviation from this behavior is a sensitive probe for supramolecular lipid structure. In studies of this type, ultrasonic velocity measurements are often used to calculate adiabatic compressibility (= $1/c^2\rho$). Ultrasonic velocity in the component phases is one of the most important variables in predicting the velocity of sound in an emulsion, and even the slight variation reported here would lead to considerable differences between spectra. Fortunately, many of the instruments designed for ultrasonic particle sizing can also be used to measure the ultrasonic velocity of a pure liquid. So, it will often be unnecessary to rely on published data. The speed of sound in water has a maximum at approximately 75°C, while that of oils decreases monotonically with temperature. The speed of sound in oil is equivalent to that in water at approximately 20°C.

The ultrasonic attenuation coefficient is a measure of how much ultrasound is dissipated in an oil per unit distance. The attenuation coefficient has little direct value beyond predicting the ultrasonic properties of an emulsion. However, in this application, a precise value is essential, and direct measurement is obviously the preferred method. The attenuation coefficient increases with frequency, at a single temperature, which is usually expressed as a power law function: α = $\alpha_0 f^{\alpha_1}$, where f is frequency (MHz). Typical values of α_0 and α_1 at 19.4°C are 1.0–1.9 and 1.7–1.8, respectively (9) (castor oil has a much higher attenuation, $\alpha_0 = 11.0$). Attenuation and its frequency dependence tend to decrease with increased temperature, and the power law relationship may no longer be appropriate (10) and predictions of $\alpha(f, T)$ cannot be made to adequate precision. If direct measurements are not available, some data sources are suggested in Table 3.

Specific heat. Specific heat is a measure of the energy required to raise the temperature of a unit mass of material. It is believed to be largely independent of the molecular weight for oils, but it does increase with unsaturation (14). The values for oils are less than half that of water. The specific heat of oils has often been observed to increase linearly with temperature (13,18), and this approach is used to model the data presented here. Other workers have observed nonlinear increases at higher temperatures ($T > 70^{\circ}$ C) (11,12); however, this may be due to autoxidation reactions. The specific heat of water has a minimal value at approximately 8°C and increases slightly at higher or lower temperatures.

TABLE 3 Literature Sources for Temperature and Frequency (*f*) Dependence of Attenuation Coefficient for Edible Oils

			_ /
Oil	t (MHz)	T (°C)	Reterence
Safflower, soy, peanut, rape	0.5-18	0–60	10
Sperm whale, seal	1.5-60	5-55	24
Castor, olive, peanut, safflower, rape	2–95	19.4	9
Coconut	1–5	20-25	35
Olive	1–5	25-60	36
Olive, castor	3.15, 3.95	0-55	37

Density and thermal expansion coefficient. The density of a material is a measure of the mass per unit volume. The density of most food oils is less than that of water. In general, the density of an oil decreases with molecular weight and increases with unsaturation (14). Several workers (many citations are provided in Ref. 34) have developed empirical functions to relate vegetable oil density to fatty acid composition and temperature. The density of water has a maximum at approximately 4°C and then decreases with further increases in temperature. The density of oil decreases linearly with temperature.

The thermal expansion coefficient defines the fractional changes in the volume of a material with temperature. Its value increases approximately linearly with temperature for liquid oils. The thermal expansion coefficient of water is zero at the density maximum (\sim 4°C) and increases approximately linearly on either side of this value. The thermal expansion coefficients of water and oil are equal at approximately 40°C.

Viscosity. Viscosity is a measure of intermolecular friction in a fluid and hence of its resistance to flow. Food oils behave as ideal Newtonian liquids over a wide range of shear rates and therefore may be characterized by a single viscosity. Viscosity of oils decreases exponentially with increasing temperature, which is modeled here by an Arrhenius-type equation. More complex polynomial equations have been developed for specific samples (26), but intersample variability means that the enhanced precision implied is generally unjustified. The viscosity of water is much less (~2%) than that of most oils (Fig. 1).

Thermal conductivity. Thermal conductivity describes the ease with which heat passes through a material. It is a particularly difficult parameter to measure, and consequently there are few values reported for food oils. A tabulation (23) of largely single-temperature measurements (made between 4 and 35°C) reported values of $\tau = 0.156-0.176 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$

(mean 0.167, $\sigma = 0.008$, n = 9) and no apparent dependency on temperature. Similar data for cottonseed oil were obtained at 25°C, $\tau = 0.172 \text{ W} \cdot \text{m}^{-1}\text{K}^{-1}$ (13). Kaye and Higgins (22) showed that thermal conductivity of olive oil decreases slightly in a linear manner with temperature (0–200°C): $\tau =$ 0.1676 – 6.00 × 10⁻⁵T, n = 11, $r^2 = 0.999$. In the absence of more complete information, it is reasonable to accept this correlation for all oils. This correlation is plotted alongside the corresponding values for water in Figure 1. At all temperatures, water is a much better conductor of heat than oil.

Appendix: Temperature dependence of the physical properties of water. The ultrasonic velocity, specific heat, and thermal conductivity of water can be calculated from the general equation (6,7):

$$X = \sum_{i=0}^{n} k_i T^i$$
[5]

where X is the parameter of interest, and k_i are constants listed in Table 4. The other parameters are defined by specific equations (7):

$$\log \eta = \frac{1301}{\sum_{i=0}^{3} k_i (T - 20)^i} - 1.30233$$
[6]

Viscosity, >20–100°C:

$$\log \eta = \frac{k_1 (20 - T) + k_2 (20 - T)^2}{T + 105} \log \eta_{20}$$
^[7]

where η_{20} is the viscosity at 20°C calculated from Equation 7 (= 1.002 mPa·s).

Density:

$$\rho = \frac{\sum\limits_{i=0}^{5} k_i T^i}{1 + k_6 T}$$
[8]

The thermal expansion coefficient can be calculated from constants used in Equation 8 by the same approach taken with the oil above. The relevant constants, k_i , for these equations are listed in Table 4.

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TABLE 4

Constants to Predict Thermophysical Properties of Water from Equations 5-8

	I /						
	k_0	<i>k</i> ₁	k_2	k ₃	k_4	k_5	k_6
$c (\text{m} \cdot \text{s}^{-1})$	1.40238754E + 03	5.03711129	-5.80852166E - 02	3.34198834E - 04	-1.47800417E - 06	3.14643091E - 09	
$Cp (J \cdot kg^{-1} \cdot \circ C^{-1})$	4.1762	-9.0864E - 05	5.4731E – 06	0	0	0	0
$\rho (\text{kg} \cdot \text{m}^{-3})$	9.9983952E + 02	1.6945176E + 01	-7.9870401E - 03	-4.6170461E - 05	1.0556302E – 07	-2.8054253E - 10	1.6879850E – 02
$\tau \ (W {\boldsymbol{\cdot}} m^{-1} {\boldsymbol{\cdot}} {}^{\circ} C^{-1})$	5.7109E – 01	1.7625E – 03	-6.7036E - 06	0	0	0	0
$\eta \text{ (mPa·s)} (T < 20^{\circ}\text{C})$	9.98333E + 02	8.1855	5.85E – 03	1.30233			
η (mPa·s) ($T > 20^{\circ}$ C)	1.3272	-1.053E - 03					

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