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Dressings and Sauces

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I. INTRODUCTION

Dressings and sauces include mayonnaise, spoonable and pourable salad dressings, condiment sauces (e.g., ketchup, barbecue sauce, spaghetti sauce). The Association for Dressings and Sauces (ADS) reports the U.S. sales of dressings (including mayonnaise) in 2000 was $2.9 billion (U.S.) with a growth rate of 3.9%.

Food dressings vary widely in their composition, texture, and flavor. A listing of some of the most widely known dressings and their fat compositions is given in Table 1. Dressings cover a broad spectrum of oil–water composition and some products are defined on the basis of their oil content. In the United States, standards of identity require that mayonnaise contain at least 65% vegetable oil by weight (some brands of mayonnaise contain 80% or more oil), a minimum of 2.5% acetic acid (vinegar for microbial preservation; citric and malic acids may also be used provided they are not greater than 25% of the weight of acetic acid), and egg-yolk-containing ingredients which may be liquid, frozen, or dried (the yolk provides emulsifying properties and, in addition, gives the mayonnaise a pale yellow color). Spoonable salad dressings may be very similar to

Table 1 Typical Fat Contents of Dressings and Sauces

Sample	Percentage
Mayonnaise	75–84
Italian	50–60
Salad dressing (spoonable)	30–60
Blue cheese	30–40
French	36–40
Russian	30–40
Thousand Island	30–45
Italian (low calorie)	0–3
Barbecue sauce	1–2
Ketchup	0.1–0.2

mayonnaise, but the standard of identity for these products requires a minimum of 30% vegetable oil and allows the use of starches as a thickening agent (products generally contain 35–50% oil). Pourable salad dressings, such as French dressing, may contain less oil and may contain gums (1).

The Nutrition Labeling and Educational Act of 1990 (NLEA) allows for nutrient content claims on the food labels in the United States. The U.S. regulations for foods are published each year in Code of Food Regulations 21 CFR Part 101. The three claims of particular interest here are Reduced, Low, and Free as applied to calories, sodium, fat, saturated fat, and cholesterol. Additionally, the NLEA standardized the serving sizes for each product. Table 2 provides the definitions of these claims. Standards vary by country.

Some fat-free salad dressings contain no oil and are not even emulsions. For the purpose of this chapter, all “full-fat” dressings and sauces are considered as “classic” emulsions and their corresponding reduced-fat and fat-free counterparts are considered as “nonclassic” emulsions. The rationale behind this classification as opposed to the one based on fat level is that all so-called nonclassic emulsion-based products need to be formulated and processed to approach in attributes to their corresponding classic emulsion-based counterparts. This need for matching the attributes presents its own unique and difficult challenges. In other words, challenges in making a 6% fat Ranch dressing are quite different than the challenges in making a 6% fat mayonnaise. This chapter includes a special section on challenges encountered with nonclassic emulsion based dressings and sauces.

Table 2 Nutrition Labeling and Educational Act Claims

Claim	Definition	Example
Reduced	A nutritionally altered product contains at least 25% less of a nutrient or 25% fewer calories than a reference food	Reduced calorie (25% fewer calories than reference food) Reduced sodium (25% less sodium than reference food)
Low	A reference amount (and 50 g of food if reference amount is small) contains $\leq$40 cal, $\leq$140 mg of sodium, $\leq$3 g of fat, $\leq$1 g of saturated fat, and $\leq$15% of calories from saturated fat, or $\leq$20 mg of cholesterol	Low calorie ($\leq$40 cal per reference amount of per 50 g, if the reference amount is $\leq$30 g or 2 tablespoons, whichever is greater) Low saturated fat ($\leq$1 g of saturated fat per serving or 50 g, whichever is greater, and $\leq$15% calories from saturated fat)
Free	A serving and the reference amount contains no or physiologically inconsequential amount: $<$5 cal, 5 mg of sodium, $<$0.5 g of fat, $<$0.5 g of saturated fat, and $<$0.5 g trans fatty acids, $<$2 mg of cholesterol, or $<$0.5 g of sugars	Fat free ($<$0.5 g per serving) Sodium free ($<$5 mg of sodium) Sugar free ($<$0.5 g of sugars)

A. Microstructure of Dressings and Sauces

There is limited literature on the microstructure of sauces and dressings. Chang et al. (2) used, transmission electron microscopy (TEM) to examine the interfacial film surrounding emulsified lipid droplets in diluted samples of mayonnaise. They concluded that the film or membrane is composed of coalesced low-density lipoprotein of egg yolks and microparticles of egg yolk granules. They postulated that the stability of the lipid droplets is attributed to the high degree of plasticity of particles and to fibrous membranes on droplet surfaces.

Tanaka and Fukuda (3) demonstrated using scanning election microscopy (SEM) that the addition of xanthan gum to French salad dressing inhibited lipid droplet fusion, which extended the shelf life up to 6 months. Tung and Jones (4), using light and electron microscopy, determined particle size (lipid droplet) in mayonnaise and a spoonable, starch-based salad dressing. The interfacial film on lipid droplets of diluted mayonnaise was described. The morphology of the continuous phase could not be determined, however, because of the preparation techniques that were used. Using SEM, they were able to describe the nonlipid material found between droplets of a spoonable salad dressing (Fig. 1). Flukiger (5) studied internal phase volume dependence in mayonnaise using light microscopy. It was shown that clumping of lipid was dependent on the concentration of emulsifiers.

Darling and Birkett (6) studied the role of fat crystallization in the reduction of emulsion stability in oil-in-water emulsions. Using freeze-fracture TEM, they showed the mechanism by which fat crystals penetrate the interfacial membrane resulting in the breakdown of the emulsion.

The application of confocal scanning laser microscopy (CSLM) has enabled Heertje et al. (7) to perform optical sectioning of mayonnaise. This instrument allows a disturbance-free observation of internal structure with relatively minor preparative steps for the sample. [Nine parts of a mayonnaise sample were mixed with one part of a Nile Blue solution (0.1%) and the stained mayonnaise was placed between two glass slides for observation.] The lipid droplets within the sample were tightly packed together, causing the outline of the droplets to be hexagonal in shape. Although the continuous phase was easily distinguishable, its structural components could not be determined because of relatively low resolution caused by magnification limitations.

Through a slight modification of an agar microencapsulation technique developed by Salyaev (8) (see also Refs. 9–11), high-resolution TEMs of liquid and visocous samples in their near-natural or native states can be achieved.

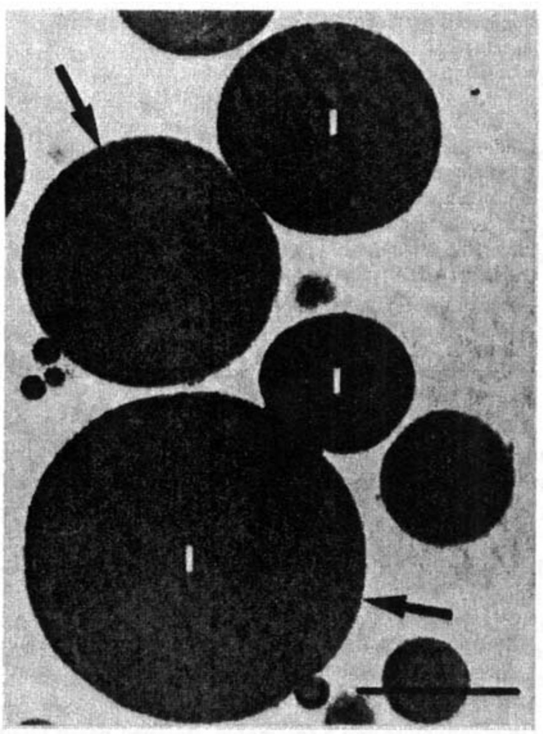

Figure 1 Salad dressing containing 49% oil viewed with scanning electron microscopy. Lipid droplets (l) are embedded within a reticulum of amorphous and fibrillarlike (arrows) material. The amorphous material is assumed to be cooked starch paste. Scale bar equals 10 µm. (Courtesy of Dr. Marvin A. Tung.)

B. Rheology of Dressings and Sauces

The discussion in this chapter will concentrate on applications to dressings and sauces and will not address the basic concepts which have been discussed elsewhere (see, e.g., Chapter 4 in F. 12, and Ref. 13). The techniques used for rheological evaluation of dressings and sauces have depended on the nature of the particular products.

Most dressings and sauces exhibit viscoelastic rheological behavior, although some ‘‘thinner’’ products are primarily viscous in their flow behavior. Mayonnaise and spoonable (or semisolid or viscous) salad dressings are examples of products which show viscoelastic rheological behavior and also possess a yield stress. Pourable salad dressings, such as French salad dressing varieties and Thousand Island dressing, are primarily viscous in their flow behavior, but exhibit varying degrees of thixotropy and often a measurable yield stress as well.

C. Stability of Dressings and Sauces

The emulsion stability of food dressings is a relative concept. All emulsions in dressings are thermodynamically unstable and, given enough time, will separate. Therefore, the formulator is fighting a losing battle and can never develop a dressing with an indefinite shelf life. Indeed, the destabilization may even be involved in the release of flavor and the perception of mouthfeel. In addition, there are different types of emulsion stability. Some emulsions are formulated to give maximum stability against coalescence (mayonnaise) whereas other emulsions are formulated to give maximum stability against creaming (pourable salad dressings). Flocculation or aggregation, considered as instability in dispersion science, may actually be desirable in dressings and sauces.

In some emulsions, maximum stability is desired to keep product integrity under adverse conditions (e.g., mayonnaise with an internal phase volume of 80%, which is past the point of hexagonal close packing of spheres at 74.05%). In other emulsions such as Italian dressing, only short-term stability is necessary.

There are three main methods for stabilizing emulsions based on electrostatic, steric, and particle stabilization mechanisms. The theoretical treatments of these mechanisms are considered elsewhere (see Chapter X). In this chapter, a brief outline of the mechanisms and their relevance to salad dressings will be discussed.

D. Processing of Dressings and Sauces

Many of the dressings and sauces, being emulsions, involve an emulsification step. The energy imparted varies with the type of product—the desired droplet size being of primary importance. Shear, turbulence, and cavitation alone or in combination are involved. Different types of emulsification device are employed, colloid mill being the most common. This section is added to this revised edition to discuss key factors controlling this critical unit operations and present guidelines for the selection of emulsification equipment.

E. Nonclassic Dressings and Sauces

Many of the dressings and sauces are high in fat and of nutritional concern to the consumers. As a result, the Better-For-You segment of these products is growing. As the fat is reduced or eliminated and replaced by other nonlipid ingredients, the need to match the appearance, texture, mouth-feel, flavor, and performance (in recipes, if relevant) attributes of the nonclassic products with their classic counterparts presents unique challenges. The prevalent thinking during the early development of fat-free products was that one must look for the magic replacement ingredient that delivers all characteristics of fat. This was subsequently replaced by a systems approach where specific technologies are leveraged for different functions of fat to create a system that works in a synergistic fashion. The most critical remaining challenge to be overcome in the nonclassic dressings and sauces is around flavor—deliver the right flavor impact and maintain its stability over the shelf life of the product.

II. MICROSTRUCTURE OF DRESSINGS AND SAUCES

A. Introduction

The tools and techniques used to investigate the microstructure of foods are vast and in some manner only limited to the imagination and creativity of the investigator. Relatively simple methods based on routine light microscopy techniques have been demonstrated by Flint (14), where she separates methods based on what information is being sought in the investigations of food emulsions. If the ingredients present in a product are the main focus, the methods can allow for significant disruption of the product, selected optical setup (i.e., polarized optics) and selective stains (i.e., Oil Red O, toluidine blue, iodine) and result in a quick diagnosis. If, on the other hand, the information being sought requires the product to remain intact, other methods are demonstrated using vapors such as iodine for starch and osmium tetroxide for oils. For these methods, the samples are prepared just prior to observation and the degree of success is in part based on the skill and experience of the investigator.

Other methods utilizing only slightly more sophisticated light microscopes employ the use of fluorescence optics. The sample preparation times can be as simple and quick as those for routine light microscopy but with the added specificity of molecular markers that can detect minute concentrations of minor emulsion components. A detailed description of fluorescence microscopy as a technique applied to food systems can be found in Ref. 15.

An example of the use of fluorescence microscopy being used to investigate the proteins at the interface of emulsions can be found in the work of Sengupta and Damodaran, although this work is not specific to dressings and sauces, the methodology could just as easily be adapted to these food systems. The authors used epifluorescence microscopy to demonstrate phase separation of mixed-protein films. By labeling each protein with a different fluorescent compound, the authors were able to demonstrate that the initial saturated monolayer exhibited a homogeneous mix of proteins but films that were allowed to age for several days exhibited a redistribution of the proteins at an air–water interface.

To answer questions not addressed by the previously described techniques requires a significant increase in time and capital investment. Although the use of fixatives and embedding materials has allowed for thin sections of emulsions to be routinely achieved, the investment in sample preparation time and tools to perform the methodology is significant. Such methodology does, however, allow one to address new and possibly more challenging questions. The introduction of glutaraldehyde and plastic embedding resins opens the door to fine-structure analysis that can take advantage of transmission electron microscopy as well as light microscopy observations.

Again, as with the light microscopy methods described earlier, the details of the methodology employed is greatly dependent on the questions being asked. The use of agar to entrap mayonnaise prior to fixation and embedment was sufficient in the work of Tung and Jones (4), where the lipid droplets and their associated interfacial film were the main focus of study even though the long-range microstructure was lost.

Other more elaborate techniques have been developed in an attempt to preserve long-range structure. One such method, developed by Salyaev (8), was designed for preparation of liquid, semiviscous, and viscous samples. The critical element in this beautifully simple technique is the production of small, delicate, agar cylinders within which the sample is placed. The cylinders are then sealed at both ends and processed intact for examination using standard methods. Samples processed in this manner remain in their natural or near-natural morphological state and the introduction of artifact is kept to a minimum. The best example of well-preserved morphology is with mayonnaise. Using this method, the tightly packed lipid droplets retain their hexagonal morphology when viewed in cross section (Fig. 2a).

Confocal laser scanning microscopy (CLSM) has the advantage of allowing multifocal plane imaging of intact, often unprocessed samples. Although used extensively in the biomedical realm, its use in food science has been more slowly embraced. Heertje et al. (7) showed its potential in food systems, and, later, they (17) demonstrated its usefulness in studying the dynamics of emulsifier displacement at an oil–water interface. More recently and as an example of how microscopy data can

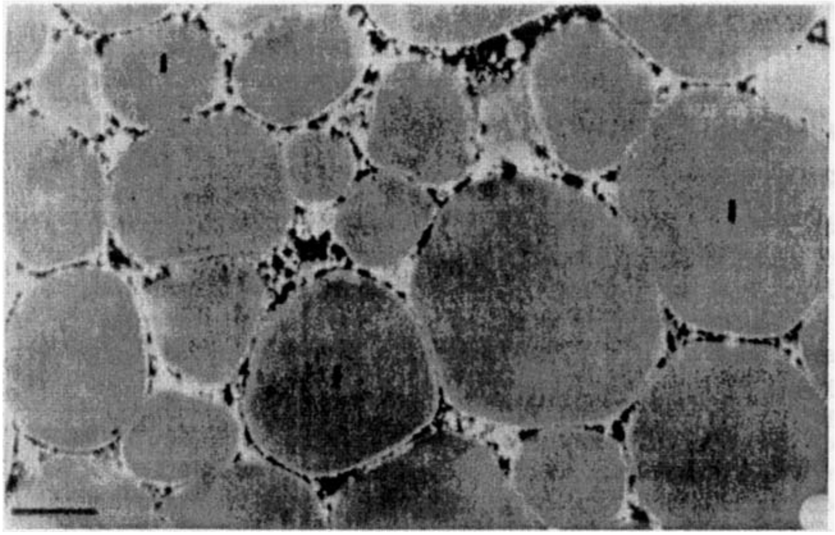

Figure 2 The microstructure of mayonnaise containing 80% oil. Low-magnification transmission electron micrograph showing the tight packing of lipid droplets (l) within sample. Note electron dense material between droplets. Scale bar equals 2 μm. (Courtesy of R. S. Unger.)

benefit from incroporation in a multifaceted approach utilizing image analysis and rheological and sensory data, Langton et al. (18) studied texture variations in mayonnaise. They varied the homogenization and temperature levels, as well as the amount of egg yolk to produce products that had defined organoleptic differences and then analyzed them using CLSM and freeze-fracture TEM methods. Whereas, CLSM utilized intact wet samples and the freeze-fracture TEM method utilized a quick-freeze method, they both avoid the more typical methods that disrupt the sample or allow for extensive repositioning of mayonnaise components. The authors were able to correlate fat droplet size and egg yolk distribution with storage modulus and perceived texture.

The most common morphological feature of dressings and sauces is the lipid droplet. Although there is great variation in the size of the droplets (Table 3), all are coated with an interfacial film. When viewed in profile at high magnification with an electron microscope, the interfacial film appears as a thin electron-dense band. The width of the film ranges from 100 to 200 Å depending on the type of sauce or dressing. An aqueous phase surrounds the lipid droplets. This phase is continuous and,

Table 3 Lipid Droplet Size in Dressing and Sauces Determined by Light Microscopy

Sample	Size[a] (μm)	Variance
Blue cheese	10.8	±6.06
Thousand Island	14.8	±7.05
Russian	35.8	±20.98
Italian (low calorie)	26.2	±13.13
French	38.0	±19.17
Italian	41.3	±28.24
Salad dressing (spoonable)	1.96	±1.37
Barbecue sauce	13.19	±3.31
Mayonnaise	2.64	±1.97

[a] Size measured as mean diameter.

in dressings, contains the spices and plant material that enhance flavor of the product.

Polymorphic masses of starch are present in the continuous phase of some spoonable salad dressings (Fig. 3). In mayonnaise, fragments of egg yolk granules are the predominant structure in the continuous phase. These fragments or particles adhere to the interfacial film and to each other, resulting in the formation of a protein network. The network increases the viscosity of the product and enhances stability of the emulsion. Sauces such as ketchup and barbecue sauce contain a low percentage of lipid and a high percentage of water and plant material. In ketchup, the plant material is presumed to be tomato cell walls. As a result of processing, the cellulose fibers that once comprised the cell walls become disassociated from each other and form a fine network that can only be visualized with the electron microscope.

B. Mayonnaise and Spoonable Salad Dressings

Mayonnaise is an oil-in-water emulsion that is difficult to examine ultrastructurally because of its high lipid content (Table 1) and the fragility of its interfacial film. Special techniques (described earlier), must be employed to avoid the introduction of artifact caused by specimen preparation. Properly prepared mayonnaise will contain lipid droplets that are tightly packed together and hexagonal in shape (Fig. 2). Lipid droplets in the sample examined have a mean diameter of 2.64 μm (±2.0 SD, Table 3) and are surrounded by an interfacial film that is approximately 140 Å in width (Fig. 2). The continuous phase, located between lipid droplets, is composed of electron-dense particles in an aqueous environment. The particles are

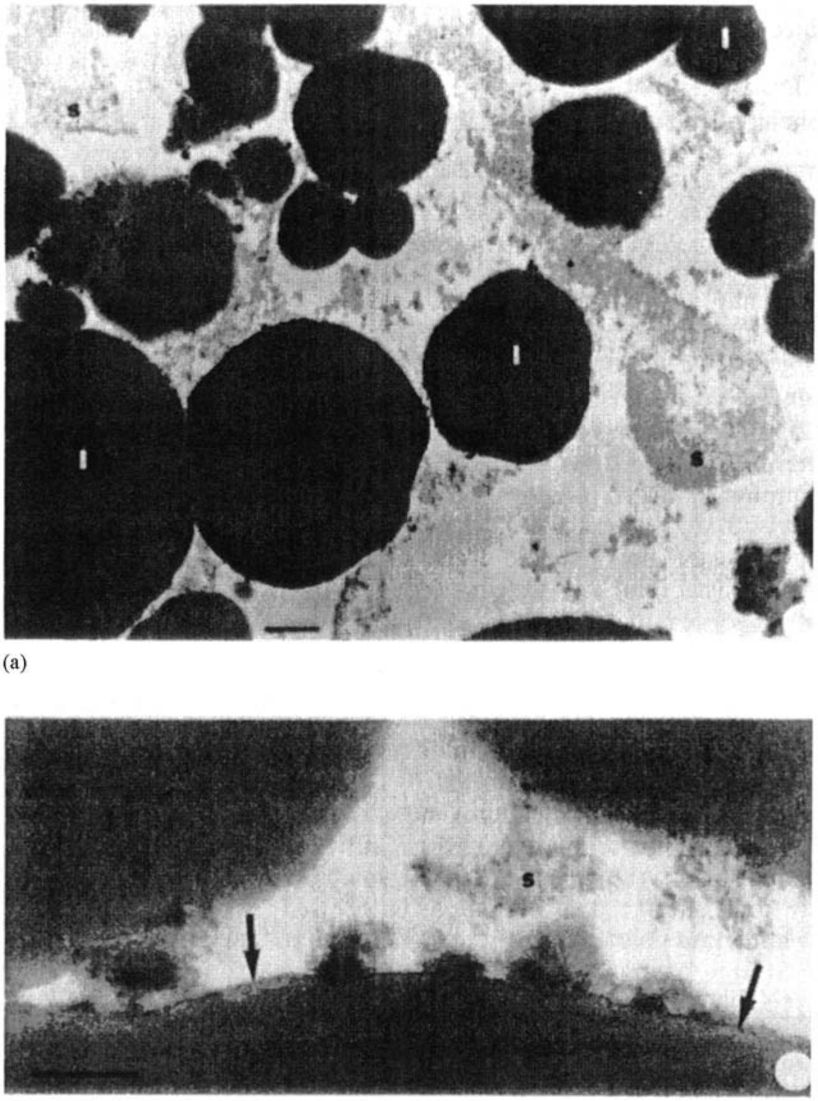

Figure 3 The microstructure of starch-stabilized salad dressing. Low-magnification transmission electron micrograph showing the wide size distribution of lipid droplets (l) within the sample. Note aggregates of starch (s) with the continuous phase. Scale bar equals 1.0 μm. (Courtesy of D. Dylewski and R. Martin.)

polymorphic in shape, average 550 Å in size, and are presumed to be fragments of egg yolk granules. The protein particles adhere to one another, forming "bridges" between lipid droplets and also forming a layer or coating on the interfacial film. The protein bridges undoubtedly influence the rheological properties of mayonnaise, and the coating of the film should enhance emulsion stability.

The spoonable salad dressing examined in this study is an oil-in-water emulsion that contains 46% lipid (Table 1). Some spoonable salad dressings have a starch base. Lipid droplets in these samples are spherical to angular in outline and have a mean diameter of 1.9 μm (Table 3). The interfacial membranes are continuous, approximately 120 Å in width, and appear electron dense. Polymorphic aggregates of starch are present in the continuous phase (Figure 3). At high magnification, small particles of starch adhering directly to the interfacial membrane can be resolved. The presence of starch in the continuous phase is thought to increase the stability of the emulsion.

C. Pourable Salad Dressings

Pourable salad dressings are emulsions that share one common morphological feature, the lipid droplet. Because lipid droplets frequently and rapidly coalesce, depending on the type of dressing, morphological descriptions are difficult from a technical standpoint. Phase separation further adds to the difficulty and can only be overcome by using methods that are rapid. Differential interference light microscopy and freeze-fracture transmission electron microscopy are the methods of choice.

The lipid droplets are spherical in shape, surrounded by an interfacial film of various widths and composition, and vary in size (Table 3). Lipid droplet size is specific for each type of dressing and is determined by the stabilizers used and the method of processing.

Based on lipid droplet size, the pourable salad dressings examined in this study can be divided into two classes. Blue cheese, Ranch, and Thousand Island are included in the first class of "creamy dressings" with droplets that range from 10 to 15 μm in size or even lower. The second class contains droplets that are from 25 to 40 μm in size and includes "oily dressings" such as Russian, Italian, and French dressings.

D. Sauces

1. Ketchup

The samples of commercial ketchup that were examined were composed primarily of tomato cell fragments (Figs. 4a and 4b). Large fragments of

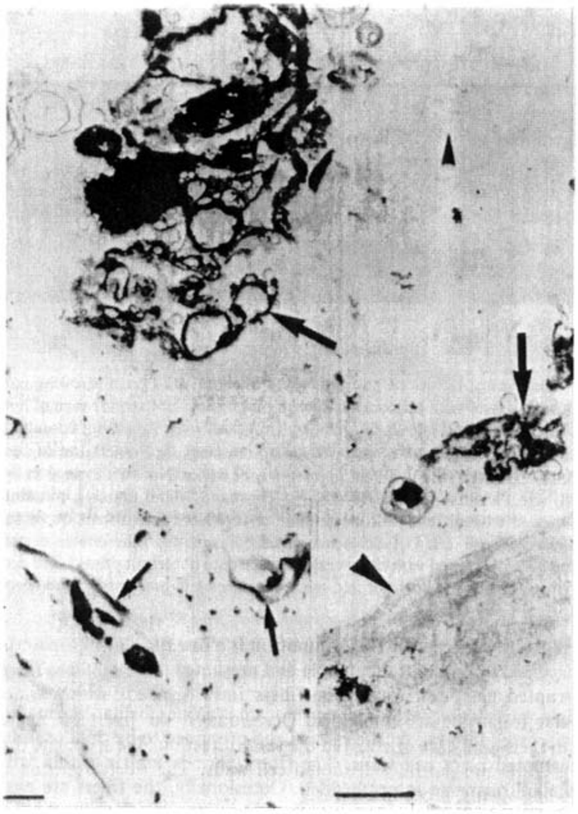

Figure 4 The microstructure of ketchup. (a) Light micrograph of a thick section showing tomato cell fragments (arrows). Scale bar equals 10 µm. (b) Transmission electron micrograph showing aggregates of plant cell fragments (arrows). Note: Cell fragments appear to be embedded within a matrix of fine fibrillarlike material (arrowheads). Scale bar equals 0.5 µm. (Courtesy of D. Dylewski and R. Martin.)

cell walls and aggregates of intercellular material all within the size range of 10 µm or less could be resolved using light microscopy. Although the ketchup was known to contain 0.1% oil, distinct droplets were not detected in the sample.

Examination of thin sections using TEM revealed the presence of a major structural/functional component of ketchup that was not resolvable at the light microscopic level. This component is a fine fibrillarlike material that is dispersed throughout the sample and presumed to be cellulose fibers

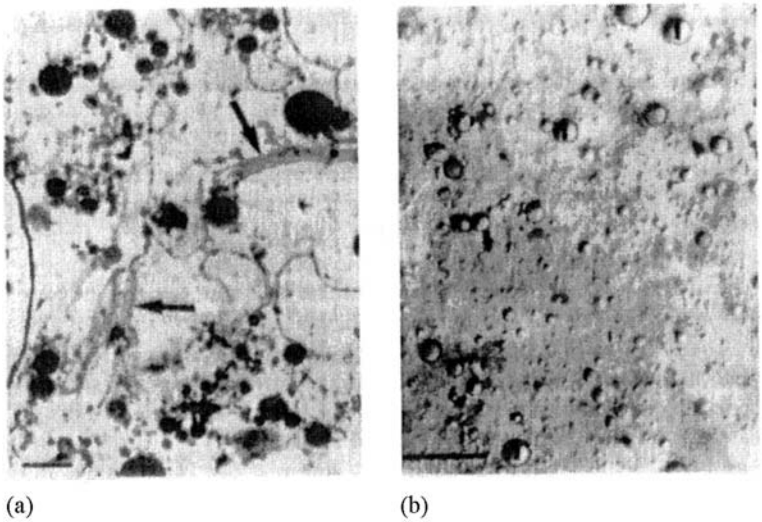

Figure 5 The microstructure of barbecue sauce containing 1.5% oil. (a) Thick section of sample viewed with bright field light microscopy. Lipid droplets (l) appear to be entrained within plant cellular debris (arrows). Scale bar equals 10 µm. (b) Differential interference micrograph showing fine dispersion of lipid droplets (l). Scale bar equals 50 µm. (Courtesy of D. Dylewski and R. Martin.)

from disrupted plant cell walls. The fibers form a matrix within which intracellular fragments are embedded. Occasionally, the fibers are aggregated with their long axes oriented in the same direction. We speculate that these aggregates are partially disrupted cell walls. The fibers function as water-binding agents, much like gums.

2. Barbecue Sauce

The barbecue sauce presented in this study is an emulsion that contains approximately 1.5% oil (Table 1). The mean diameter of the lipid droplets is 13.9 µm (Table 3), and they appear spherical in shape (Figs. 5a and b). The continuous phase of the sauce is composed primarily of plant cell fragments, presumably cell walls of tomatoes.

III. RHEOLOGY OF DRESSINGS AND SAUCES

A. Introduction

Over a very long time, Heinz ketchup commercials have depicted the thickness of their ketchup as an important and differentiating quality attribute versus the competition. Barbecue sauces have, time and again, touted thickness as a good thing. Indeed, consumer acceptance of dressings and sauces is at least somewhat dependent on their texture. One very important reason to measure the rheology of dressings and sauces then is because the rheological properties are related to the product texture.

Texture of dressings and sauces is very complex, multidimensional term and consumer liking of product texture is an overall effect stemming from evaluations across all relevant textural attributes. In fact, as depicted in some Heinz ketchup commercials, the slowness with which the ketchup pours out of a bottle gives a visual assessment of the product thickness (textural attribute) and viscosity (rheological attribute). Thus, multiple senses are involved in the assessment of texture. Hence, the need for many different approaches and techniques to measure the rheological behavior of these products.

Even when considering a single attribute, and a simple one at that, such as thickness, the perception of that attribute is a combination of several different ways in which the attribute can be perceived. As discussed by Borwankar (19), consumer perception of the thickness of barbecue sauce is a combination of perception of viscosities from several different sensory cues: how the sauce pours out of the bottle, perception during basting, its cling, and, finally, its mouth-feel. Because the steady-state rheological behavior of the sauce is non-Newtonian, the viscosities relevant in these different applications are different because different shear rates are relevant (Fig. 6). This highlights the central difficulty encountered when one attempts to draw correlations between rheology and sensory perception: For a reasonable chance of success, only one means of sensory assessment of the texture attribute should be emphasized, a feat not easily accomplished in practice.

Perhaps the most emphasized viscosity characteristic for dressings and sauces is the viscosity relevant in the mouth. According to Shama and Sherman (20), the relevant shear stresses and shear rates involved are dependent on the product's viscosity itself, ranging from very high shear rates

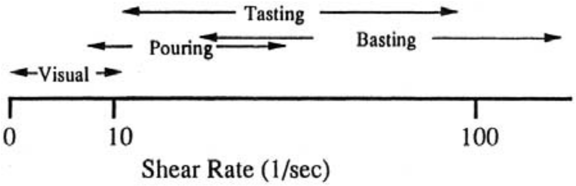

Figure 6 Shear rates operating under different processes involved in sensory perception of barbecue sauce.

corresponding to the shear stress of about 100 dyn/cm^2 for very thin systems to shear rate of about 10 s^{-1} for very thick systems. For typical pourable dressings and sauces, the shear rate range in question is about to s^{-1}. For spoonable dressings, firmness or thickness is perhaps more related to the yield stress rather than viscosity.

A more complex but often mentioned textural attributes, again especially for spoonable salad dressings, is creaminess. Creaminess likely has more than just textural connotations. Even as a textural term, its sensorial assessment is complicated and not fully understood. Nevertheless, Kokini (21) suggested that creaminess is determined by thickness and smoothness, which he modeled via fluid mechanical models. He obtained a reasonably good correlation between creaminess and rheological properties across several product categories.

B. Rheological Measurements

Viscosity is the characteristic most commonly used in salad dressing quality control (22) and the rheology of dressings and sauces has been the subject of many articles. Although these have appeared in a number of scientific and technical journals, the reader is referred especially to the *Journal of Texture Studies* and the *Journal of Dispersion Science and Technology*.

The techniques used for rheological evaluation of dressings and sauces have depended on the nature of the particular product. For viscoelastic mayonnaise or spoonable salad dressings, various authors have employed creep compliance (see, for example, Refs. 23–28) and other dynamic testing (see, for example, Refs. 29–32). Coaxial cylinder viscometers and extrusion rheometers have been used to evaluate both the viscoelastic products and the more fluid dressings and sauces (see, for example, Refs. 33–34).

Atkin and Sherman (23), from creep compliance studies, found that mayonnaise exhibits nonlinear viscoelastic behavior at stresses of about 10,000 dyn/cm^2. Later, Kisseoglou and Sherman (25) concluded from creep compliance measurements at about 70 dyn/cm^2 that mayonnaise exhibited linear viscoelastic behavior. Gladwell et al. (38) studied the dependence of the rheological behavior of soy oil in water emulsions upon oil concentration and Gladwell et al. (39) studied the dependence of the creep/recovery behavior of oil-in-water emulsions upon disperse phase concentration. In each of those studies, regions of linear viscoelastic behavior and regions of nonlinear viscoelastic behavior were also found. This illustrates the importance of carefully specifying the measurement conditions. Similarly, Rao (40) noted that Boger and Tiu (41) observed time-dependent shear thinning (thixotropic) behavior with mayonnaise, were Blake and Moran (33) did not. Rao (40) gave that example to demonstrate the necessity for determining whether a given sample has time-complicating factor in the measurement of viscosity of thick systems such as mayonnaise is the occurrence of wall slip effects. The presence of these have been demonstrated by Pascual et al. (42), who recommend the use of serrated configurations to minimize these and improve the reproducibility of measurements.

Although Barnes and Walters (43) have argued convincingly that "…given accurate measurements, no yield stress exists," the yield stress concept is useful in characterizing many dressing and sauces. As quoted by Barnes and Walters (43), Scott Blair (44) defined yield stress as "that stress below which no flow can be observed under the conditions of experimentation." Following this definition, various dressings and sauces do exhibit yield stresses when one considers the "conditions of experimentation" to be the conditions of use by the consumer. Although many different ways are available for measuring the yield stress of a spoonable salad dressing, perhaps the simplest method is the vane method. This methid is best described by Alderman et al. (45). Park, et al. (46) (see also Ref. 47) used a falling-needle viscometer and a rotating-concentric-cylinder viscometer to determine the yield stress of several samples, including tomato ketchup. The falling-needle viscometer data led to a yield stress of $10.85\,\mathrm{N/m^2}$. Perhaps the best technique to measure the yield stress of pourable dressings such as Ranch is using a controlled-stress rheometer.

Recently, a spate of new rheological methods is being applied to food systems, especially dressings. Accounts of extensional viscosity measurements and tribology (thin layer) measurements are appearing in the literature (see Refs. 48 and 49, respectively). These are emerging areas and the significance of these rheological properties for food scientists and engineers will become clearer as these techniques are more widely utilized.

C. Emulsion Rheology

For a good overview of emulsion rheology, refer to the work of Sherman (12, Chapt. 4; 50, 51). A general representation of viscosity of emulsions can be written as

$$\eta = f(\eta_0, \phi, d, A) \tag{1}$$

where η is the viscosity of emulsion, η_0 is the continuous phase viscosity, ϕ is the phase volume fraction of the dispersed phase, d is the drop size, and A is the state of aggregation of the emulsion. This equation is a very good way of thinking about emulsion viscosity, although it clearly is a simplification. The emulsion viscosity increases with the phase volume fraction of the dispersed phase in a non-linear manner. The phase volume fraction of the dispersed phase includes contribution from the thickness of the emulsifier layer whose contribution increases as the drop size decreases.

The effects of drop size and aggregation are primarily seen with relatively concentrated emulsions ($\phi > 0.2-0.4$). The viscosity of the emulsion decreases with increasing drop size. This is due to a number of reasons: hydrodynamic resistance dependent on the average separation distance between drops, contribution from interfacial rheology, electroviscous effects, increased aggregation seen in finer emulsions, and contribution of interfacial layer thickness mentioned earlier.

Aggregation increases the emulsion viscosity. The interdroplet interaction determines if the aggregates are relatively open or compact. Open aggregates entrain large amounts of continuous phase and hence have higher viscosity than the compact ones. Open aggregates occur when there is a strong attractive interaction between droplets, and compact aggregates are formed when the attraction is weak (see Ref. 52). The aggregation state of an emulsion is clearly dependent on the shear rate and, for thixotropic (time-dependent) system, on shear history. As the shear rate increases, aggregates are broken down to smaller and smaller sizes and the emulsion viscosity decreases. Hence, concentrated emulsions often show a shear thinning (non-Newtonian) behavior.

Thus, the shear thinning seen in dressings and sauces is attributable to progressively breaking aggregates with shear. Gums and stabilizers can play a role as well (see Section IV.C). The time-dependent or thixotropic behavior arises if the kinetics of breaking and forming aggregates is slow. Chan Man Fong and De Kee (53) have modeled this behavior and shown that the model explains transient rheological properties of mayonnaise fairly well. Amemiya and Shoemaker (54) have shown that, for model dispersions, thixotropy increases with increasing phase volume fraction and decreasing drop size.

The viscosity of emulsion increases as the continuous phase viscosity increases. Typically, gums and stabilizers are added to pourable dressings and salad dressings to increase the continuous phase viscosity and, hence the viscosity of the emulsion. Gums and stabilizers have non-Newtonian rheology and they impart non-Newtonian character to the emulsion even when the amount of the dispersed phase is low.

Equation (1) can actually be generalized to any rheological property, not just viscosity. For yield stress and shear modulus of concentrated emulsions, Princen (55) derived equations theoretically that directionally confirm the drop size and phase volume fraction effects. In their model, which did not account for aggregation, yield stress and shear modulus are a result of packing the emulsion beyond the close-packing limit. Aggregation can actually produce finite yield stresses and shear moduli even below the close-packing limit. Similarly, gums and stabilizers if added can have yield stress and shear modulus as well themselves.

The above discussion actually suggests that aggregation can be used to one's advantage in formulating dressings and sauces. An aggregated system will have a higher viscosity than a nonaggregated system. Thus, one can formulate a dressing (or a sauce) with less oil and/or less gums and stabilizers by causing controlled aggregation. As discussed in Section IV and in other chapters in the book, aggregation leads to an increase in creaming and coalescence. The control lies in devising an aggregated system that is otherwise stable to creaming and coalescence.

IV. EMULSION STABILITY OF DRESSINGS AND SAUCES

A. Introduction

Dressings cover a broad spectrum of oil–water composition, as is seen in Table 1; from mayonnaise, a 65–84% oil-in-water emulsion, to fat free dressings, which may contain no oil. Most commercially important sauces contain little oil and, therefore, will not be considered in this section.

Dressings also cover a diverse range of products. For discussion purposes, dressings are divided into three categories: semisolid, pourable, and nonclassic. Each category has its own requirements for emulsion stability, but each product shares the need to maintain the emulsion integrity during processing, packing, transportation, storage, consumer preparation, and consumption. Of these dressings, only mayonnaise, salad dressing, and French have their own standard of identity. Mayonnaise must have at least 65% fat and salad dressing and French dressing must have 30% and 35% fat, respectively. The oil phase volumes of these and other dressings are evident from viewing Figs. 1–5.

As previously mentioned, the emulsion stability of food dressings is a relative term due to the fact that all emulsions in dressings are thermodynamically unstable and, given enough time, undergo phase separation. However, in a kinetic sense, the emulsions in dressings can be made stable through an acceptable shelf life and still maintain appearance, texture, and flavor that are desirable to the consumer. For individual dressings, emulsion stability may be concerned with any or all aspects of flocculation, creaming, and coalescence. The half-life of dressing emulsions may range from seconds for a product like separating Italian dressing to years for mayonnaise.

B. Theoretical Considerations

As discussed in Chapters 1 and 2, the primary modes of destabilization of emulsions involve creaming, flocculation, and coalescence. These processes occur concurrently and tend to build upon each other. Coalescence is promoted in cream layers and in flocs. Coalescence and flocculation lead to increased creaming rates. Differential creaming promotes flocculation. Although traditionally considered as a mode destabilization in dispersions, flocculation or aggregation is not necessarily bad in itself. Flocculation can, in fact, be beneficial if it does not lead to visual separation and/or coalescence. This is because aggregation leads to increased rheological properties and, thus, can provide a cost-savings opportunity (see above).

Emulsions are typically stabilized against creaming by the use of stabilizers such as gums and starches. The primary factor leading to stability is the increase in continuous phase viscosity, which can proportionally reduce creaming velocities, and, at times, the presence of a yield stress, which can completely suppress creaming. Gums are known to actually promote aggregation by either bridging or depletion mechanisms, depending on whether the gum attaches to the interface or not. Nevertheless, the suppression of creaming due to increased continuous phase rheological properties far exceeds any increase caused by promotion of aggregation.

Stability toward coalescence in the emulsions derives from the use of emulsifiers which are surface-active agents and/or particles. For coalescence to occur, the drops must encounter each other and the thin film trapped between the drops plays a crucial role. The drainage and stability of the intervening thin film controls whether or not coalescence will occur in such encounters. The film can be stabilized either by reduction or elimination of the driving force due to repulsive interactions between droplets that can counteract the forces that are pushing the drops together or by slowing down the drainage rates.

Kinetic stability against coalescence can be obtained via a decrease in the rate of drainage of the intervening thin films due to suppressed interfacial mobility. This is achieved either due to persistence of interfacial tension gradients that suppress mobility, the Gibbs–Marangoni effect, and/or the interfacial viscoelasticity [see, for example, the reviews by Ivanov, (56), Ivanov and Dimitrov (54), and Wasan (58)]. These changes reduce the rate of drainage of the thin film between emulsion droplets, thus suppressing coalescence. Although there has been considerable amount of work done on drainage and subsequent rupture of thin films, the timescales involved in these processes are so short (seconds to minutes in most reported studies) that the kinetic mechanism is likely not important in providing the shelf stability to dressings and sauces.* Rather, one relies on changing the interaction between the droplets by enhancing repulsion. The primary means of stabilization are electrostatic, steric, structuring and particle stabilization. Several of these mechanisms are commonly recognized and are also described in Chapter 1 and are only briefly covered here. Perhaps the one exception is structuring, which will be described in Section IV.B.3. These stabilization mechanisms rely on altering the interactions between droplets to render emulsions metastable.

1. Electrostatic Stabilization

The attractive forces of the van der Waals interactions and the electrostatic repulsion forces due to the diffuse electrical double layer are the basis for the DLVO (Derjaguin, Landau, Verwey, and Overbeek) theory of colloid stability.

The electrostatic repulsive force is derived from the local accumulation of counterions at a charged surface, the concentration of these ions being strongly dependent on the ionic strength (a function of salt concentration and valence of the ions) of the medium. The thickness of the diffuse layer of counterions around the charged particle surface is compressed by the salt and hydrogen ion concentrations normally found in dressings to such a degree as to make the repulsive force ineffective in stabilizing the emulsion. Even though complex ionic surfactants such as proteins are commonly used, their method of stabilization extends beyond that of electrical repulsive forces and will be covered in the next section. Therefore, electrostatic stabilization plays only on indirect role in dressing emulsion stabilization by its effect on protein structure.

2. Steric Stabilization

As two emulsion droplets approach closely, the adsorbed surfactant layers interact. For macromolecules adsorbed to the surface of emulsion droplets, only a portion of the large molecule is at the surface. Much of hydrated structure remains in the aqueous phase. Therefore, as two emulsion droplets with adsorbed macromolecules approach each other, the chains of the macromolecules interact in at least two ways. First, the number of configurations that the molecular chains can attain is reduced (along with their

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*On the other hand, this mechanism is likely to be very important in the formative stages of the emulsion in preventing recoalescence (see later). The studies of thin film drainage in the early stages of emulsion formation are lacking due to the inherent difficulties involved. However, recently, some of the nonequilibrium effects involved have been investigated.

entropy). Additionally, the hydrated portion of the chains has associated water molecules which, when forced from the chain, create a local osmotic gradient (increases the enthalpy) which tends to force the particles apart.

For small-molecule nonionic emulsifiers, the lack of hydrated structures extending from the surface reduces the entropic and enthalpic forces until they are often too weak to provide adequate stability. However, small-molecule nonionic emulsifiers such as the polysorbates are used in pourable dressings with good results. Here, stabilization may instead be caused by the structured packing of micelles in the continuous phase between approaching droplets.

3. Structuring

In Chapters 1 and 2, the formation of liquid crystals was considered as one of the ways that emulsifier structures can stabilize emulsions. A relatively new mechanism recognized over the last decade or so is the stratification phenomena seen in various systems. The presence of micelles, particles, or similar discrete entities in the bulk can lead to stratification in the thin films separating emulsion droplets. This phenomenon has been discovered and developed by Wasan, Ivanov, and co-workers (see, for example, Refs. 58–60). The ordered structure occurs in thin films and leads to a stabilizing interaction. This has been shown to occur in food dispersions as well (61).

4. Particle Stabilization

Emulsions can also be stabilized by adsorption of particles at the droplet interface (62). It is the balance of energies at the solid–liquid and liquid–liquid interfaces which determine the effectiveness of the particle stabilization. In other words, both the oil and the water phases should prefer contact with the solid particle rather than with each other. Theoretically, the optimum stabilization occurs when the oil and water phases have equal preference for the particle and the contact angle at the droplet surface is 90°C. For practical purposes though, the contact angle should be between 60 and 70°C to overcome instability which could result from perturbations at the interface. Contact angles can be changed by adding surfactants which adsorb preferentially to one interface.

Particle stabilization is thought to be present in several dressing systems. For example, in dressing systems, finely ground spice particles such as mustard have been attributed to enhancing emulsion stability. Also, in mayonnaise, small particles from the egg yolk have been attributed as providing the major stabilizing force.

C. Emulsifiers and Stabilizers

As discussed later in Section V, the formation of droplets in dressing emulsions has little value if the droplets are not protected from coalescence by emulsifiers (the half-life of emulsions without emulsifiers is about 1 s). Typically, stabilization is divided into two processes: transient (at the time of formation) and long term (over shelf life). Small-molecule surfactants seem to impart better transient stability (due to their ability to migrate along the droplet surface), whereas large-molecule surfactants function best at long-term stability. However, surfactants are seldom additive in their effects on emulsion stability. In fact, when more than one surfactant is present, they compete for the interface. Under equilibrium conditions, the surfactant with the greatest ability to lower the interfacial tension is preferentially adsorbed, and if present in sufficient quantity to cover all available interfacial area, it can effectively prevent adsorption of other surfactants. Small molecules often adversely affect the long-term storage because they preferentially adsorb to the interface and inhibit absorption of the large-molecule surfactants, which are actually better at providing long-term stability.

Three general types of surfactants are used in dressings: substituted polysaccharides, polyoxyethylene derivatives of sorbitan fatty acid esters (polysorbates), and proteins (Table 4). The substituted polysaccharides such as propylene glycol alginate are used in various salad dressings to provide low levels of emulsion activity and stability. Low-molecular-weight surfactants such as the polyoxyethylene derivatives of sorbitan fatty—acid esters—the polysorbates [high HLB (hydrophile–lipophile balance)] are used in pourable dressings, where greater emulsion stability is desired. Proteins are present in many dressing emulsions and are an important class of food surfactant. The manner in which proteins absorb and rearrange at the droplet interface is critical to emulsion stability.

Table 4 Sources of Emulsifiers

Emulsifier type	Ingredients
Protein	Buttermilk, sour cream, skim milk, nonfat dry milk, whole milk, sodium caseinate, whey, whole eggs (fresh, salted, frozen), egg whites (fresh, frozen, dried), egg yolks (fresh, salted, sugared, dried)
Phospholipids	Egg yolks, whole milk, sour cream
Particle	Mustard flour
Synthetic	Polysorbate
Chemical modified	Propylene glycol alginate

Proteins form a film around the surface of oil droplets to give stable oil-in-water emulsions. The interfacial activity of a protein proceeds through the following stages: (1) native protein molecule diffuses to the interface, (2) protein penetrates the interface, and (3) molecules rearrange to achieve minimum energy. Stage 1 of emulsification by proteins is a diffusion-dependent process; therefore, any variables such as temperature, shape of the protein, and viscosity of the medium will affect this stage. In stage 2, the protein molecule arrives at the oil–water interface and causes a reduction in interfacial tension as it establishes the interface. As a general rule, the interfacial tension should be lowered below 10 dyn/cm for effective emulsification to take place (63).

After the proteins establish the interface, a slow change in interfacial tension with time is observed. Graham (64) explains that this change is a consequence of the molecular rearrangements within the protein film. Rearrangement is fast for flexible proteins, such as casein, and slow for rigid globular proteins, such as lysozyme. Interfacial films from globular molecules have more residual structures, such as helices, therefore allowing more cross-linking and chain entanglement. This greater extent of cross-linking and entanglement produces a greater resistance to shear and dilation, thus resulting in greater resistance to shear and dilation thus resulting in greater viscoelasticity and stability. Globular proteins tend to form more cohesive films than flexible proteins. Films containing globular proteins will be more stable than films containing flexible molecules because lateral cohesion of the globular proteins will tend to heal defects in the films. For prevention of coalescence in protein-stabilized emulsions, the pH should be away from the isoelectric point and the interfacial layers need to be heavily hydrated and electrically charged. The role of the thickness of the protein layer, however, is a point of controversy.

As already mentioned, mayonnaise has an extremely high dispersed oil phase volume ranging from around 75% to 82% in commercial samples. Due to this high dispersed volume, the droplets are mostly in contact with each other and the spherical shape of the oil droplets has become deformed until the drops actually resemble the polyhedral figures seen more often in foams. Obviously, whatever forms the barrier between adjacent droplets must be mechanically strong, rugged, and present a high-energy barrier to coalescence. There are two mechanisms left to impart stability to the emulsion: steric and particle. For steric stability, macromolecular surfactants such as protein are needed. For particle stability, particles with a polar portion for water and a nonpolar portion for the oil (perhaps a complex of lipid/polar-lipid/protein) are required. Fortunately, a natural emulsifier exists which contains components for both methods of stabilization—the egg. Typically, the batch process for making mayonnaise involves starting

Table 5 Polysaccharides and Their Use in Dressings

Gums/starches	Comments
Xanthan	Most widely used gum; salt, acid, and heat resistant; suspending agent; stabilizer; gelling reaction with locust bean gum and guar gum
Sodium alginate	Gels with Ca^{2+} ions; high viscosity with heat
Propylene glycol alginate	Stabilizer; emulsifier; thickener; some gelling with Ca^{2+} ions; pH tolerant;
Locust bean gum	Thickener; gels with xanthan; insensitive to Ca^{2+} ions
Guar gum	Thickener; insensitive to Ca^{2+} ions; cost-effective
Gum arabic	Some emulsifier activity; thickener; stabilizer
Gum acacia	Suspending agent; forms films at interface
Starch	Thickener; retrogradation a problem
Modified starch	Inhibits retrogradation; thickener
Microcrystalline cellulose	Adds body and mouth-feel

with an aqueous phase of egg yolks, vinegar, salt, sugar, and mustard grains to which vegetable oil is added slowly until a seed emulsion of desired viscosity is formed. Then, the remainder of the oil may be incorporated rapidly.

Gums and/or starches (see Table 5) are added to most dressings for a variety of reasons. These polysaccharides are not surface active (with the exception of PGA) but act to thicken the dressing which affects mouth-feel, cling, and so for (refer to Section III. C). Most importantly, stabilizers can improve the emulsion stability of the dressing. Of course, by making the continuous phase more viscous, oil droplets encounter each other less often. More importantly, it is the creation of a yield stress which increases emulsion stability by minimizing or eliminating creaming of the oil droplets under the relatively low force of gravity (65).

D. Natural Ingredient Effects

1. Eggs

There have been numerous studies on eggs and egg yolks, with regard to their composition as well as the emulsifying properties. For an excellent review, the readers are referred to Refs. 66 and 67. Egg yolks are the most functional components of the whole egg as far as the emulsifying functionality in dressings and sauces is concerned. Egg yolk owes its emulsifying activity to a lecithin protein complex (lipoproteins). Egg whites (albumen) are less functional. Egg yolk is a suspension of particles in protein solution. Although liquid egg yolk has been a standard raw material for decades, many suppliers today are promoting egg yolk powders with excellent flavor and functionality. Today's egg yolk powders owe this to a gentle spray-drying process used that prevents heat abuse. The egg yolk powders have longer shelf life and do not deteriorate in performance and taste when stored correctly. These can be readily hydrated prior to use.

Egg yolk contain components which contribute to emulsion stability by both steric and particle mechanisms. The particle mechanism is evident in mayonnaise in the micrograph shown in Fig. 2, where protein particles are found at the interfaces between oil droplets. The isoelectric point of egg whites and egg yolks are 5.4 and 5.3, respectively (68). At neutral pH these egg fractions are negatively charged but at the pH's of most salad dressings (pH 2.8–pH 4.0), they are positively charged. However, due to the rather high ionic strengths of dressings due to high salt content, electrostatic stabilization is not likely.

2. Mustard Flour

Salad dressings typically contain mustard flour. Chang et al. (2) note that, according to Corran (69), powdered mustard is an effective emulsifier.

Fischbach and Kokini (24) examined the effects of variable mustard flour levels on oil-in-water emulsion stability and rheology. They found that adding lower levels, (up to 0.5%) of mustard flour increased stability, but higher levels of mustard flour (0.75% and 1.0%) led to decreased emulsion stability, possibly due to formation of a xanthan gum–mustard protein complex. Creep parameters also reached a maximum at lower levels of mustard flour, depending on the age of the emulsion. Mustard flour is added to products for its flavor contribution, but it is also thought to contribute to emulsion stability, possibly by a particle mechanism.

3. Dairy Proteins

Today, more and more salad dressings contain dairy ingredients incorporated in them. Dairy proteins are mainly of two kinds: caseins and whey proteins. Depending on the dairy ingredient used, whey proteins may or may not be included. If cheese is used, proteolytic fractions of caseins may be included. All of the caseins and a whey protein, α-lactalbumin, have an isoelectric point in the range of 4.1–4.5 (70). The other major whey protein, β-lactoglobulin, has an isoelectric point of 5.3. As a result, the environment of many dressings is very close to the isoelectric point of these proteins and these proteins may be nonfunctional as emulsifiers in dressings. Worse yet, they may compete with the functional emulsifiers such as egg yolk for the interface and actually cause emulsion stability issues.

E. Practical Considerations

As previously mentioned, in order to more easily understand the characteristics and requirements of emulsion stability for food dressings, it is worthwhile to consider dressings as three categories: semisolid, pourable, and reduced-calorie dressings.

Semisolid dressings are, by definition, very viscous emulsions (refer to section III. C). In mayonnaise, this is due to a high phase volume of oil, whereas in salad dressing, the effect of phase volume is augmented through the use of stabilizers (starches) which thicken the continuous phase. Due to the high oil content of the mayonnaise emulsion, the oil droplets are forced close together, and in extreme cases, the spherical shape of the droplets becomes deformed (see Fig. 2). This close proximity precludes concern for flocculation, and emulsion stability must instead be concerned with preventing coalescence. Because in may cases droplets are actually in contact with neighboring drops, coalescence can only be delayed by employing tough, pliable membranes around the oil droplets. In semisolid dressings, this membrane is formed from protein and polar lipid components of egg yolk.

Pourable dressings are, of course, much less viscous than semisolid dressings and as such are susceptible to creaming. The oil phase volume normally ranges from 30% to 50% oil, but can be as high as 60–65% for the creamy style dressings. Due to this lower ratio of oil to water, the oil droplets are spaced apart from each other and flocculation, which could lead to coalescence, is also of concern.

Low-fat and fat-free dressings are generally based on the full-fat dressings with the addition of starches and gums to replace the oil. Of course, as the oil is reduced, the emulsion stability does not become a problem; however, maintaining the low amounts of oil in a fully dispersed state throughout the dressing can be challenging in lower-viscosity pourable dressing types. Special considerations have to be given to imparting a full-fat flavor and texture for these products as well. These are considered in more detail in Section VI.

A prediction of the food emulsion's stability without actually going through shelf life is very desirable. Typical measurements have evolved around accelerated aging tests but must be viewed carefully because many forces caused by the "aging" test would have never been experienced by a normally aged emulsion. One must realize that the accelerated physical stability tests do not consistently accelerate many processes occurring through normal aging (e.g., oxidation and hydrolysis), which are just as important in determining product shelf life. Nevertheless, the assessment of emulsion stability is often necessary. A typical protocol for assessing product's emulsion stability should include several methods: shelf-life testing at normal storage temperature, abuse testing at elevated and/or colder temperatures than normal to simulate warehouse and consumer abuse and abuse testing vibration to simulate distribution abuse; perhaps even freeze–thaw cycles. Accelerated testing such as the centrifugal test may be used as well, but with the above caution. The science behind the various tests is not completely understood, making them an art rather than truly scientific, but, often times, practitioners have developed enough product experience that well-designed abuse tests can serve them well.

There is a real need for a more scientific prediction of emulsion stability, especially as new products and cost-reduced products are developed at a frantic pace. Common methods based on the partitioning behavior of surfactants such as HLB and PIT (phase inversion temperature) are of little use in most dressing systems. This is because the major stabilizing forces are usually due to proteins and adsorption of small-molecule surfactants interferes with their adsorption. Currently, of the four most promising areas of predicting emulsion stability, two are based on properties of the interface between the oil and water. For years, the correlation of interfacial rheology and emulsion stability has been claimed, but as discussed, the suppression of the drainage rate that the interfacial rheology causes is not large enough to provide long shelf stability. More recently, Darling and Birkett (6) have given acclaim to the thickness of the interfacial layer as a predictor of emulsion stability. The new area of structuring in the thin film is likely to emerge as the most definitive predictor of stability. The final predictor of emulsion stability is based on particle size and distribution and how these change over time. It is actually an old method, but due to recent refinements in resolution, it allows the researcher to follow coalescence in its earliest stages.

The challenge to the food emulsion scientist is to comprehend the food system on its many levels—not only those of emulsion science (molecular structure of surfactants; assemblies and aggregates at the interface and in the bulk; rheology; and stability) but their consequential effect on the organoleptic properties of the food as well (correlated with sensory evaluation).

V. PROCESSING OF DRESSINGS AND SAUCES

The primary goal of emulsion processing for dressings and sauces is to produce a uniform, physically stable product with desired textural attributes. Although emulsion processing often has its greatest effect on product texture and stability, important changes in product flavor, color, and sheen may also occur. In general, reducing the mean internal-phase particle size and narrowing the particle size distribution will increase product stability, viscosity, and yield. However, smaller oil droplets also refract light differently than larger droplets and will result in a product that is lighter in color and greater in opacity. Additionally, smaller oil droplets may release flavors differently than larger oil droplets, possibly reducing the intensity and delaying the impact of flavor as the product is tasted. Therefore, the benefits of producing a more stable product by reducing droplet size must be weighted against the impact of texture, flavor, and color.

As discussed by Walstra (71), breakage of the larger droplets into smaller ones is not the only process occurring during emulsification. Many other processes occur simultaneously. Adsorption of the emulsifier on to newly formed droplet surface is a key process that needs to occur during the timescale of emulsification, otherwise the newly formed droplets that are not adequately stabilized by the emulsifier will recoalesce and all the disruption is for a naught. In order to adequately stabilize the newly formed emulsion droplets against recoalescence, first and foremost the emulsifier must be present in sufficient quantity to provide minimally monolayer coverage on the interface and, second, the monolayer coverage must be reached during the timescale of the emulsification process. If the adsorption is too slow, recoalescence cannot be prevented.

Thus, as described in Fig. 7, drop breakage, emulsifier adsorption, and recoalescence of the droplets are the three processes of importance. The final droplet size of the emulsion is governed by the balance of the breakage and the recoalescence processes. The droplet breakage is primarily governed by the time, amount, and distribution of energy input into the system. The recoalescence step is primarily impacted by the type, amount, and adsorption kinetics of the emulsifier. Efforts to optimize emulsification must account for the interdependencies between the functional properties of the emulsifier and the processing equipment.

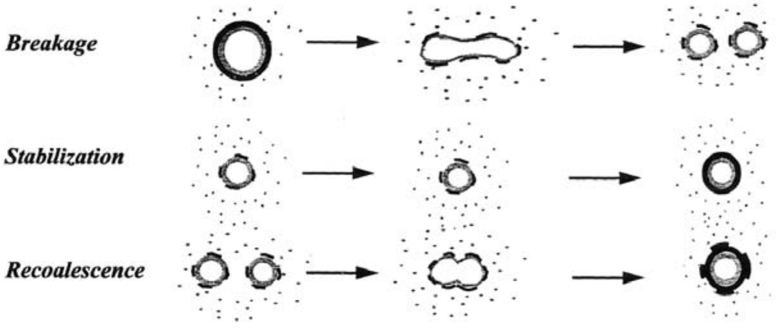

Figure 7 Processes occurring during emulsification. (Adapted from Ref. 71.)

The main steps in an emulsification process are (1) preparation of the oil and aqueous phases with proper incorporation of emulsifiers, hydrocolloids, and other dry ingredients, (2) mixing the phases to form a uniform premix, which may be in the form of either a coarse emulsion or an unstable dispersion, (3) applying shear or other forces to form droplets of the internal phase and reduce the mean droplet size, and (4) allowing sufficient time in the shear zone to adequately cover the internal phase with emulsifier to stabilize the droplets. With the correct emulsifier, food emulsions can be produced with very little mechanical energy input; dressings and sauces have been prepared for hundreds of years using no more than a bowl and a whisk. However, the use of more complex emulsification devices enables product attribute optimization at the lowest cost. Generally, dressings and sauces that are dispersions as opposed to emulsions (typically low- and no-fat dressings and sauces) may be produced on the same process that is used to produce emulsions, although different considerations may take priority, such as the shear rate needed to create a uniform product in the case of a dispersion being of greater importance than the amount of time in the shear zone necessary for emulsifier adsorption in the case of an emulsion.

A. Drop Breakage

Drop breakage occurs in emulsification devices under laminar, turbulent, or cavitation modes, or combinations thereof. Elongational flow is encountered under some conditions. For an excellent account of the drop breakage under these various conditions, the reader is referred to Chapter 1 of Ref. 12.

Studies carried out by Taylor (72) on single droplets under laminar conditions have shown that the drop undergoes steady deformation under shear up to a point at which breakage can occur into smaller fragments. The extent of deformation is characterized by a dimensionless number called the Weber number, We^{L}, which is defined as the ratio between the deforming shear forces and conservative interfacial forces, which tend to restore the spherical, undeformed shape of the drop:

$$\mathrm{We}^{\mathrm{L}} = \frac{\tau}{p_c} = \frac{\tau d}{4\gamma} \tag{2}$$

Here, τ is the shear stress, p_c is the capillary pressure, γ is the interfacial tension and d is the drop diameter. At a certain critical Weber number, a critical deformation state is reached at which rupture occurs.

The critical Weber number is a function of the viscosity ration of the two phases:

$$\mathrm{We}_{\mathrm{crit}}^{\mathrm{L}} = f\left(\frac{\eta_d}{\eta_c}\right) \tag{3}$$

Figure 8 shows the variation of $\mathrm{We}_{\mathrm{crit}}$ with the viscosity ratio. Thus, the maximum size of the drop that can withstand rupture is given

$$d_{\max} = \frac{4\gamma \mathrm{We}_{\mathrm{crit}}^{\mathrm{L}}}{\tau} \tag{4}$$

Equation (4) shows that selection of both the proper emulsifier to lower interfacial tension and process to provide a high shear rate will aid in achieving a small $d_{\max}$. It is also clear then that in order to cause droplet breakage under laminar conditions, the maximum droplet size that can survive rupture depends strongly on the viscosity ratio. A viscosity ratio of near unity gives the smallest droplet sizes for a given shear input and is the most energy-efficient situation.

Turbulent flow is characterized by eddies of a wide size range. Overall liquid movement is due to the large eddies of the order of the energy-transmitting device such as the agitator. These eddies transfer kinetic energy to the small eddies where viscous dissipation occurs. If a droplet in turbulent

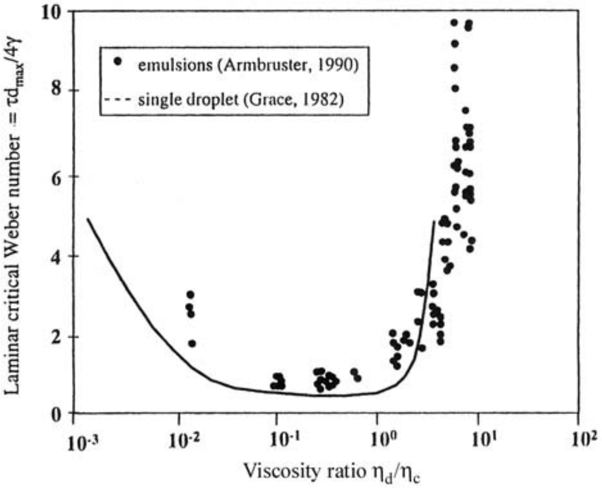

Figure 8 Variation of critical Weber number with viscosity ratio. (From Ref. 75.)

flow is much smaller than the eddy, it follows the movement of the eddy. If, however, it is of a size similar or larger than the eddy, fluctuating velocity gradients at the droplet surface cause droplet deformation, which can lead to rupture. In analogy to the laminar conditions, a turbulent Weber number can be defined as the ratio between the deforming turbulent forces and the restoring interfacial forces:

$$\mathrm{We}^{\mathrm{T}} = \frac{\rho_c v'^2 d}{4\gamma} \tag{5}$$

where ρ_c is the continuous phase density and v' is the eddy velocity. According to the Kolmogoroff theory of isotropic turbulence, we get

$$\mathrm{We}^{\mathrm{T}} \propto \frac{\rho_c \varepsilon^{2/3} d^{5/3}}{\gamma} \tag{6}$$

Rupture, again, occurs when the Weber number exceeds a critical value:

$$\mathrm{We}^{\mathrm{T}} > \mathrm{We}^{\mathrm{T}}_{\mathrm{crit}} \tag{7}$$

Thus,

$$d_{\max} \propto \frac{\gamma^{3/5}}{\rho_c^{3/5} \varepsilon^{2/5}} \tag{8}$$

Equation (8) is valid for $d_{\max}$ larger than the size of the small energy-dissipating eddies, which is commonly the case in a simple emulsification device without homogenization facilities.

When the viscosity of the system is large or the drops are very small, Shinnar (73) has suggested that the drop breakage even under highly turbulent conditions occurs due to viscous stresses rather than the inertial stresses, and

$$d_{\max} \propto \left(\frac{\gamma^2}{\rho_c \eta_c \varepsilon}\right)^{1/2} \tag{9}$$

This equation is not fully tested experimentally, perhaps because the high-pressure homogenization condition that are perhaps necessary to achieve small drops involve multiple mechanisms and not simple turbulent shear for drop breakage.

Finally, cavitation is the phenomenon of formation and collapse of small vapor bubbles in a liquid. A high-velocity fluid produces locally negative pressures which lead to the formation of a cavity at that point. As the cavity implodes, it produces a macroscopic shock were. A nearby droplet can get sucked into the shrinking void and the resultant droplet deformation may lead to its rupture. Cavitation is implicated in ultrasonic emulsification and, perhaps, in a high-pressure homogenization, although Phipps (74), has rejected this notion.

The above equations describing drop breakage assume that the drop stays in a high-energy zone for sufficiently long time for it to deform and break. This critical deformation time depends on the drop viscosity and the excess deforming stress above the conservative interfacial stress

$$t_{\mathrm{def}} = \frac{\eta_d}{\tau - p_c} \tag{10}$$

For a drop size reduction by a factor of 10, approximately 10 consecutive disruption steps are necessary, assuming that each disruption step results in two drops of size $(d/2)^{1/3}$. The overall residence time in the high-energy zone must be longer than the sum of individual critical deformation times. The influence of the residence time is particularly evident under turbulent conditions.

B. Emulsifier Effect

Given that the emulsifier is capable of stabilizing the emulsion in the first place, the conditions needed to be met to minimize recoalescence are that the emulsifier is present in sufficient quantity to adsorb on the newly formed surfaces to provide minimally a monolayer coverage and that the kinetics of adsorption are rapid. The approximate monolayer coverae for low-molecular-weight lipid based emulsifiers such as polysorbates is of the order of $5 \times 10^{-10}\,\mathrm{mol/m^2}$ and for macromolecular emulsifiers such as proteins it is of the order of $2–8\,\mathrm{mg/m^2}$. Based on the interfacial area generated, one can calculate the amount needed for adsorption. The adsorbed emulsifier is in equilibrium with the emulsifier in the bulk. If the adsorption isotherm is known, one can calculate precisely the minimum amount of emulsifier needed. Otherwise, one can add a little excess over the amount needed at the interface.

Adsorption kinetics are governed primarily by the size of the emulsifier molecule. When the emulsifier adsorbs rapidly, the situation is what is called a mechanically limited dispersion. Here, the above drop breakage equations apply, with γ being the equilibrium interfacial tension at the emulsifier concentration involved (this approaches $\gamma_{\min}$, the minimum

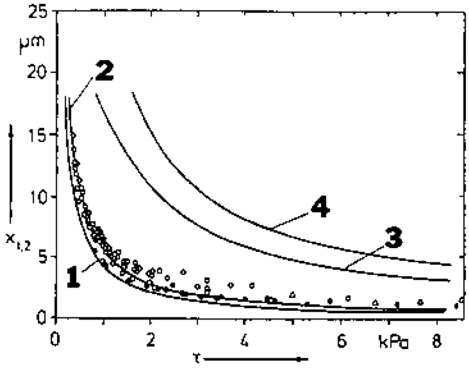

Figure 9 Droplet diameter as a function of shear stress for a fast emulsifier, LEO-10. (From Ref. 75.)

achievable interfacial tension for the emulsifier in question if the emulsifier is present in sufficient excess). When the emulsifier adsorbs slowly, the interfacial tension in the above equations is not the equilibrium interfacial tension at the emulsifier concentration involved but is, in fact, quite a bit higher, resulting in a larger drop size. This situation is described as kinetically limited dispersion. Furthermore, without sufficient adsorption of the emulsifier, the recoalescence process is not completely prevented, further increasing the droplet size obtained. Under laminar conditions, the larger emulsifier molecules show slow adsorption kinetics. Figures 9 and 10 show the droplet sizes obtained for a fast emulsifier LEO-10, lauryl alcohol 10(ethylene oxide) ether, and a slow emulsifier, egg yolk (75).* These data are the first such data known to the authors showing the effect of adsorption kinetics of emulsifier on the final droplet size obtained during emulsification.

Although it is understandable that the larger emulsifier molecules show slow adsorption kinetics under laminar conditions, Walstra (65) has suggested that the exact opposite may be applicable under turbulent conditions, especially when the emulsifier molecular sizes approach the size of the drops. The phenomenon of capture during collisions is then likely involved. Capture efficiencies are expected to be significantly higher for such large emulsifier molecules. No experimental data similar to those of Armbruster are available under turbulent conditions to verify this assertion.

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*The lines in the figures are theoretical calculations based on Eq. (4) with the area average diameter estimated to be $d_{\max}/2.4$ for critical Weber numbers estimated from the viscosity ratios (not shown).

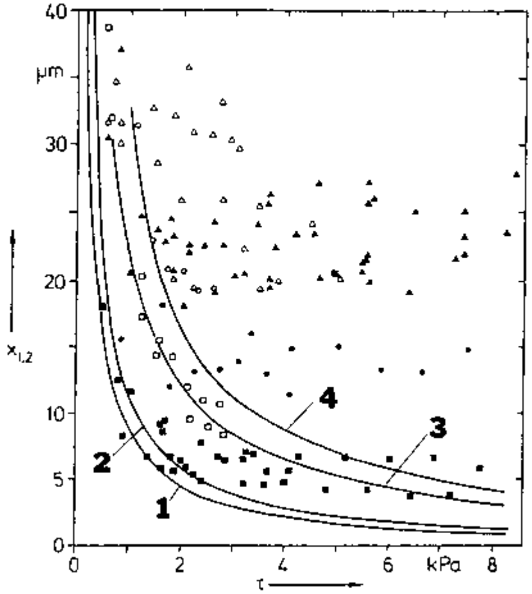

Figure 10 Droplet diameter as a function of shear stress for a slow emulsifier, egg yolk. (From Ref. 75.)

The Weber relationships discussed earlier suggest that droplet size may be reduced by (a) reducing interfacial tension and by (b) increasing process shear rate in the case of laminar flow or fluid velocity in the case of turbulent flow. However, following the above discussion, depending on whether a system is a kinetically or mechanically limited there may be limits on droplet size reduction available in a given system that will drive process developer to modify the selection and operating procedures of emulsification equipment. For example, it is possible to show that when using a homogenizer to process a slow emulsifier system at a constant emulsifier level, there exists an inverse relationship between homogenization pressure and droplet size for low-fat systems such that processing at progressively higher pressures will deliver progressively smaller droplets. However, using the same process and emulsifier systems at a higher fat level, progressively higher pressures will initially yield smaller droplets, but an asymptote will be reached where higher pressures will not reduce droplet size further. Although the initial droplet size may be the same at high pressures for the different fat levels, the extremely short residence time in the homogenizer limits the extent of emulsifier adsorption in the shear zone. Therefore, recoalescence is more likely to occur in the high fat/high surface area system resulting in an asymptotic relationship between particle size and homogenization pressure such that no further droplet size reduction is possible beyond a certain pressure. If smaller droplets were desired in a high-fat system, it would be necessary to either change the type of emulsifier or equipment to make the system mechanically limited.

C. Process Design and Equipment Selection

Important considerations in designing a food emulsion process include process type (batch versus continuous), order of addition of ingredients, process temperature, and process shear rates. The decision of whether to use a batch or continuous process is driven by consideration of run-time length, space, frequency of manual ingredient additions, and capital requirements. Processes which have a high number of product changeovers and/or a significant number of ingredient additions are ordinarily designed as batch processes. Continuous processes are typically used in cases of long run times and offer advantages of reduced labor and space requirements.

The selection of the final emulsification device that will achieve the minimum droplet size and produce the finished product is of great importance. Although the feed to this device may consist of either a coarse emulsion or an unstable dispersion, a coarse emulsion is often used. The benefit of the coarse emulsion is the partial reduction in droplet size and enhanced uniformity of feed to the final emulsification device. When preparing the feed to this unit operation, a coarse emulsion may be obtained using an emulsifier soluble in the continuous phase and adding the discrete phase to the continuous phase (typically, the discrete phase will be oil and the continuous phase will be aqueous). In a batch process, a mixing tank may be used prior to the shear device to provide the coarse emulsion. A variety of agitator types may be found in the industry, including axial-, radial-, and disk-type impellers. In continuous or semicontinuous processes, the oil and aqueous streams are joined and sheared via in-line mixers to form the coarse emulsion prior to the final emulsification device. Many in-line mixes are also commercially available for this application.

Although many choices are available for the emulsification unit operation, they generally fall into two categories: (1) devices that reduce droplet size via shear forces in laminar flow and (2) devices that reduce droplet size via cavitation and/or shear in turbulent flow (a number of devices employ both methods). Shear forces result from velocity gradients; most shear devices generate shear forces by passing fluid at high velocities through small stationary or moving gaps or by passing fluid from a region of high to low pressure. In general, a higher shear rate will produce a smaller and more uniform droplet size, although there is a point of diminishing returns and the temperature rise at very high shear rates may be detrimental to the product. Commonly used shear devices include colloid mills, toothed-disk rotor/stator mixers, and pin mixers. Colloid mills utilize a single conical rotor–stator pair in which the rotor surface geometry and the gap between the rotor and stator may be adjusted to vary shear rate. Tooted-disk rotor–stator devices generally consist of three or more sets of rotors/stators in which the tooth geometry, rotor/stator gap size, and rotor may be adjusted to modify shear rate. As discussed earlier, cavitation refers to the implosion of vapor bubbles within a fluid; the resultant shock waves create droplets. Shear generated in turbulent flow may contribute to droplet formation and size reduction due to intense fluid mixing and localized pressure differences. The most common example of this method is homogenization in which vapor bubbles are formed by pressure differential in fluid flow.

The choice of equipment may be driven by formulation. As discussed earlier, products using slow emulsifiers and high oil levels may be better suited to equipment which provides sufficient residence time to allow for droplet stabilization, whereas products using fast emulsifiers and/or low-fat levels may be better suited to equipment such as a homogenizer, which provides significant droplet size reduction with very little residence time in the unit (although for all equipment, residence time is on the order of seconds).

For oil-based dressings and sauces, attention must also be paid to minimizing oxidation of the oil content through the processing and packaging operations. In addition to formulation methods including the use of sequestrants and antioxidants, common methods include processing in an inert-gas environment and the use of barrier packaging materials to displace oxygen from the product and prevent its reintroduction.

Table 6 lists some of the product-impact parameters that should be considered when choosing an emulsification device. Manufacturing considerations such as flexibility in modifying shear rates, sanitary design, CIP ability, energy usage, maintenance costs, changeover flexibility, and ergonomics in disassembly must also be considered and may often define the choice between equipment that has similar effects on product attributes.

It is a common misconception to assume that the central role of an emulsification device is to provide energy input needed because one is increasing the interfacial area, and hence, the interfacial energy of the system. In reality, only a small fraction of the energy input actually goes toward the interfacial energy. Most of it is dissipated as heat. Estimates are that only 0.01% of the energy used in a homogenizer is converted to the interfacial energy. That is why many of the high-energy emulsification devices cause a significant temperature rise in the emulsion, sometimes necessitating a cooling scheme. In fact, a good estimate of the energy

Table 6 Criteria of Emulsification Equipment Selection

Type of machine	Agitated vessel	Colloid mill	Toothed disk dispersers	Homogenizers
Communition mechanisms	Turbulent shear	Laminar turbulent shear	Turbulent shear	Turbulent shear/cavitation
Energy consumption (W/m^3)	10^3–10^5	10^6–10^{11}	10^8–10^9	10^{11}–10^{13}
Residence time (s)	Undefined	10^{-3}–10^{-1}	10^{-3}–10^{-2}	10^{-5}–10^{-4}
Droplet size (μm)	5–100	2–20	2–20	0.5–5
Suitable for high-fat o/w emulsions	±	+	+	−
Suitable for low viscosities	−	±	±	+
Suitable for high viscosities	±	+	+	−
Addition of particulates	+	−	±	−
Indirect heating/cooling	+	±	±	−
Direct steam injection	+	±	±	−
Continuous processing	−	+	+	+
Batch processing	+	+	+	−

input by an emulsification device can be made from the temperature rise obtained if no cooling is provided or from a heat balance if cooling is provided. In the case of a homogenizer, for every 1000 psi homogenizing pressure, the temperature rise is approximately 3° F.

VI. NONCLASSIC DRESSINGS AND SAUCES

In previous sections, the full-fat versions of traditional emulsion-based products have been presented and, in this chapter, will be referred to as classic emulsions. In this section, nonclassic emulsions will be considered as no-fat to low-fat versions of standard full-fat products.

On a chronological basis, spoonable salad dressings developed in the 1930s can be considered as a first-generation, reduced fat mayonnaiselike dressing. Oil levels were reduced from 80% in mayonnaise to 45–50% in salad dressing. With this substantial reduction in dispersed phase volume, significantly thinner texture was supplemented through the use of starches. Flavor changes were masked through targeting a tarter, sweeter, and more spicy profile.

During the mid-1980s, "light" dressings were introduced. Gums were included in formulations to add texture such as mouth-feel, cling, firmness, slipperiness, and so forth that could not be provided in an acceptable manner through merely increased levels of starch.

Then, during the early 1990s, fat-free dressings were developed. In most cases, starches and gums used alone or in conjunction with each other were not able to deliver the texture and flavor necessary to gain satisfactory consumer acceptance. Fat replacers or fat mimetics were the technologies developed for the most part to provide the additional texture and appearance characterisits needed.

The progression of fat/emulsion phase reduction is readily apparent in a microscopic investigation. The loss of a significant portion of the fat in the move to fat free is evidenced in the example of spoonable salad dressings in which the increasing role of starch and fibrillarlike fat replacers are shown as the fat/emulsion phase is reduced from full fat (48%), light (23%), and fat free (2–3%) (Figs. 11–11c).

Earliest fat replacers were built on the concept of non-digestible fat like molecules. Olestra from Procter and Gamble was developed in the 1960s from sugar and fatty acids to produce sucrose hexa, hepta and octa fatty acid esters. This fat replacer was designed to replace oil on a one-to-one basis, functioning as the hydrophobic phase in emulsions and even capable of fried and cooked applications. However, its non digestibility and macro ingredient status raised issues concerning fat-soluble vitamin depletion and

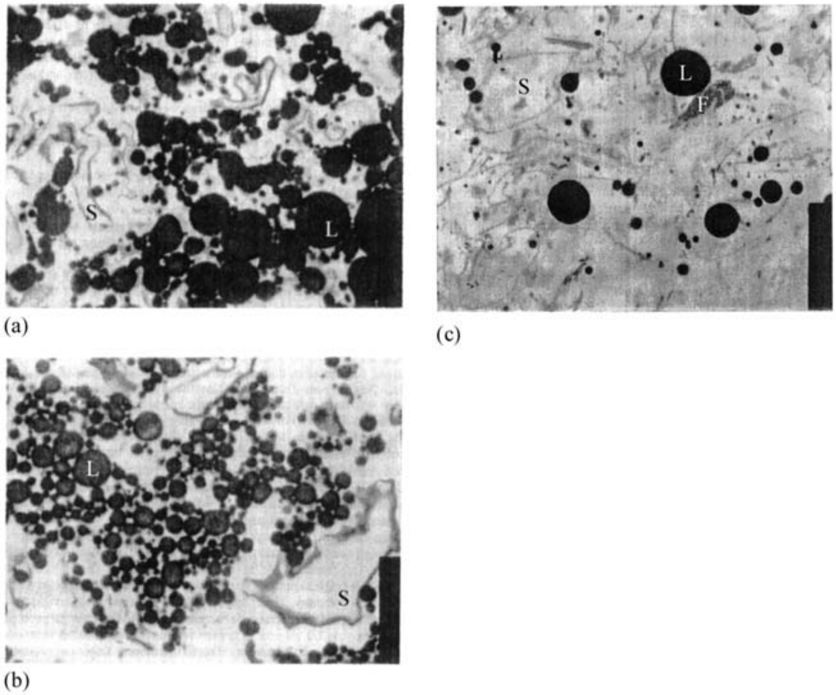

Figure 11 The microstructure of spoonable salad dressing. (a) Section of stained, full-fat sample viewed with bright-field light microscopy. Lipid droplets (l) are numerous and are separated by some starch granules. Scale bar equals 25 μm. (b) Section of stained, "light" sample viewed with bright-field light microscopy. Lipid droplets (l) are significantly less numerous and are separated by more starch granules. Scale bar equals 25 μm. (c) Section of stained, fat-free sample viewed with bright-field light microscopy. Lipid droplets (l) are scant and are separated by starch granules and fibrillarlike material. Scale bar equals 25 μm.

the body's ability to handle it as waste. A number of similar products have been developed such as esterified polysaccharides, carboxylate esters, and so forth by various companies but none of them are in use in dressings and sauces.

During the late 1980s a paradigm shift occurred such that rather than trying to replace all of the functionality of fat with a fatlike molecule, of perhaps some of the functionality of fat could be substituted through microparticulates. The original product based on this concept was Simplesse from the NutraSweet Company. Using egg and dairy protein as source materials, a creamy material was produced which was composed of spherical protein particles in the 0.5–2.0-μm diameter range. It was claimed that the particulates produced a ball-bearing effect in the mouth. Later, larger particles were also found to work if soft and compressible. This concept was soon transferred to carbohydrate-based materials and their gels. Starch and gum technologies were reevaluated and novel textures were developed to supplement conventional usages. It was this paradigm shift in the 1980s that led to the successful introduction of fat-free products.

The original approach for replacing the functionality of the fat from the emulsion phase was to search for a ''magic bullet'' ingredient which would target all the product needs. This approach was only somewhat successful in products which fat contributed in fairly straightforward and minor ways to texture and where the product had strongly characterizing flavors which were mostly independent on fat contribution or interaction. A systems approach was soon adopted to replace specific product functionality of the fat by specific fat-replacement technology. The impact of fat in the emulsion phase is evidenced in the product in appearance, texture, mouth-feel, stability, handing, and, most importantly, flavor (Fig. 12).

Flavor character, release, and stability continued to be a major hurdle in the nonclassic emulsion dressings. Fat is known to play an important role in the flavor perception of foods. It influences the temporal profile, flavor impact, perception of flavor notes, and the order of their occurrence (76). The fat replacers in use today are composed of proteins and carbohydrates, which interact with the flavor compounds differently than fat does (77,78). For example, flavors are known to bind to proteins (79) and starches (80).

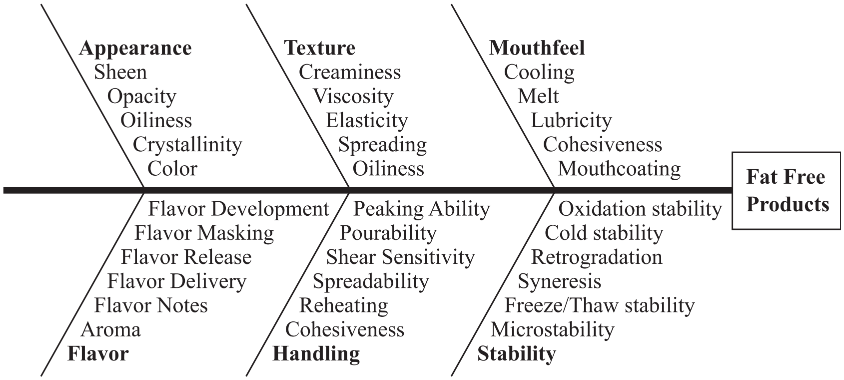

Figure 12 Functional considerations in the development of fat free products. (Adapted from *Prepared Foods*, December 1992, p. 21.)

The influence of the oil phase in the emulsion of classic emulsions on the production, perception, and preservation of flavors was considerable and presented many challenges for replication in nonclassic dressings. The near absence of fat in fat-free products posed a difficult challenge in achieving full-fat flavor (Table 1). An understanding of these flavor effects now became necessary.

The overwhelming majority of food flavors are complex mixtures of compounds. These flavors come to dressings through ingredients, product processing during manufacturing, flavor addition, chemical reactions during storage, physical changes including repartitioning of and/or loss of phases, and final food preparation.

Preception of flavor depends not only on the presence of proper flavor compounds at the appropriate intensity but the timing of the flavor release and masking effects as well. In nonclassic emulsions, the increased presence of water and the hydrophilic molecules of starch, gum, and other fat replacers dramatically affects the partitioning of volatile hydrocarbon flavor compounds. This effect significantly affects flavor intensity perception and release rates. The masking effect of the dispersed oil in the emulsion of classic emulsions plays an important role in rounding flavor perception and covering low-level off-flavors. Also, the presence of fat affects the binding of flavors by various hydrophobic sites in carbohydrates and proteins. Quality gaps in fat-free products along with low regulatory hurdles have recently opened the door for reduced-calorie fats. Products such as Caprenin and Salatrim are special triglycerides based on specific fatty acid profiles which digest at lower caloric values. These products could allow for an intermediate approach of using lower levels (but not fat free) of a fat ingredient at a significantly reduced calorie impact.

VII. CONCLUSIONS AND PROGNOSTICATION

There are four significant trends in the dressings and sauces industry. First is the introduction of increasing number of low-fat and fat-free dressings and the continuing effort to improve these products. Second is a steady launch of new products, especially new flavors, especially in sauces and pourable dressings categories. Third is the growing need to cut the cost of production. Fourth are next trends of healthy foods—for example, based on new fats and oils such as diacyl glycerols (DAGs) such as Enova oil recently introduced in the market by ADM Kao. Accomplishing this will involve changes in formulation and processing. Developing products scientifically would necessitate application of disciplines such as rheology, microscopy, and emulsion stability theory; the objective data provided by such disciplines will have to be correlated with sensory evaluation of the products.

Particularly critical is the advancement of fundamental understanding of emulsion stability. Successful predictive tests for emulsion stability can significantly reduce the product development cycle time. We believe here that the role of thin films in the stability of emulsions is an emerging field of study that is likely to be the key to predicting emulsion stability of dressings and sauces over the shelf life as well to their processing.

Microscopy of foods has come a long way in recent years. For a recent review of available techniques, see Ref. 81. Significant technical advances in the field of microscopy include cryo-fixation methods, which will replace chemical fixation with a reduction in processing time and elimination of artifacts. Expanded applications will be made of immunocytochemical methods to determine the location of target proteins in various food systems. Computer-aided image analysis and enhancement systems will allow more objective, rapid, and accurate analysis of microscopic data than current morphometric and stereological methods. Application will be made of confocal microscopy and the ''optical sectioning'' capability of that technique. The scanning tunneling microscope [and the atomic force microscope (AFM)] will be used to resolve structure at a molecular level.

Advances in theory and instrumentation have allowed rigorous viscoelastic characterization of food products. As discussed, newer techniques are being developed to characterize extensional properties and tribology of the products.

With better microscopic and rheological techniques, it will be possible to relate microstructure to rheology and, finally, sensory textural characteristics of the product, a goal which has heretofore remained elusive. These techniques, and others, will be used to understand and predict the emulsion stability of dressings and sauces.

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