Lipid emulsions

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RESUMEN

Emulsiones lipídicas

Las emulsiones son mezclas líquido-líquido con un líquido contenido en forma de gotas dentro de otro líquido. Las gotas tienen normalmente 1 μm de diámetro y las propiedades de las emulsiones dependen en gran medida de la estructura de la gota, la cual está estabilizada por las moléculas emulsionantes. La mayoría de las emulsiones alimenticias están constituidas a partir de materias primas usando un proceso de homogeneización que permite formar gotas pequeñas. El artículo describe métodos de medida del tamaño de gota y estabilidad de las emulsiones, y discute el origen físico de la textura, flavor y apariencia de la emulsión.

PALABRAS-CLAVE: Emulsiones — Estabilidad — Lípidos — Propiedades funcionales — Tamaño de gota.

SUMMARY

Lipid emulsions

Emulsions are liquid-liquid mixtures with one liquid contained as droplets within the other. The droplets are typically 1μm in diameter, and the properties of the emulsions are very dependent on the droplet structure, which is stabilised by surface-active emulsifier molecules. Most food emulsions are made from the raw ingredients using an homogenisation process to form small droplets. The paper describes methods of measuring droplet size and emulsion stability, and discusses the physical origin of emulsion texture, flavour and appearance.

KEY-WORDS: Droplet size — Emulsions — Functional properties — Lipids — Stability.

1. INTRODUCTION

Emulsions are physical mixtures of two liquids, oil and water, with one liquid dispersed as droplets within the other[1]. The droplets are known as the dispersed phase and the suspending liquid is the continuous phase. The original purpose of food emulsions was to deliver lipids in an aqueous form, as required by the digestion system. The first encounter between mammals and emulsions is their mother's milk, which is an oil-in-water emulsion designed for efficient delivery of nutrients to an infant. These natural dairy products have been mimicked by Man for hundreds of years resulting in a large array of sauces, desserts, gravies and condiments, which serve to add variety and interest to our foods.

The combination of lipid and aqueous phase also occurs in the inverse form as water-in- oil emulsions such as butter and margarine. The purpose of inverting emulsions is to restrict bacterial growth in the emulsions. Although made of the same ingredients, butter has a longer shelf-life than cream because bacteria are confined to small droplets of aqueous phase, which rapidly limits their ability to grow[2].

Although essentially oil and water, emulsions also contain a number of minor ingredients which can play a major part in the formation and stability of the product. The most important minor component is an emulsifier, or surfactant, which is a surface-active molecule that prevents the droplets from merging (coalescing) into bulk layers of oil and aqueous phase. Other additives may be included to provide flavour or colour to the emulsions, or serve to control the texture of the food. Emulsions are also vehicles for delivery of lipid-soluble nutrients to the digestive system, although the release of the specialist compounds is not always straightforward[3].

The purpose of this paper is to provide an overview of the structure and properties of food emulsions, to demonstrate the factors that need to be considered when using or designing emulsion products, and to give a comprehensive list of more detailed sources for specific information. Although many beverages are emulsions, they are generally dilute and behave as simple liquids so, with the exception of milk, they are outside the scope of the article. The reader is recommended to the excellent texts on emulsion science by Binks[4] and food emulsions by McClements[5].

2. STRUCTURE AND CHARACTERISTICS OF EMULSIONS

Most food emulsions contain droplets of diameter in the range 0.1 – 10μm, usually in a broad

distribution of sizes (polydisperse)[6]. The droplets are the key to the properties of the emulsions, and it is important to control the droplet size distribution, which in turn determines the total area of the dispersed droplets. Emulsions are inherently unstable, because the energy associated with the droplet interfaces is proportional to the total area, which is minimised when the oil and water have separated into distinct layers. All practical formulations include at least one surface-active species to act as an emulsifier, whose function is to control the separation process. Examples of emulsifiers are proteins, phospholipids and synthetic molecules such as Tweens and sucrose esters. Emulsifiers are amphiphilic molecules, comprising some hydrophilic chemical groups and some hydrophobic groups. The presence of both types of group in a single molecule means that the emulsifier is not fully soluble in either the oil or aqueous phase, and prefers to locate at the interface between the two. The adsorbed layer of emulsifier serves to reduce the interfacial energy per unit area, and it also helps to generate repulsive forces between the droplets to prevent close encounter. It the droplets are unlikely to possess enough energy to overcome the repulsive barrier when they approach each other closely, the emulsion is kinetically stable against coalescence. Coalescence is never completely prevented, and eventually all emulsions degrade to the individual components. It is the aim of the food manufacturer to formulate emulsions which do not coalesce significantly during the product shelf-life.

The droplet structure has a major effect on the properties of the emulsions. The number and interactions of the droplets determine the physical stability of the structure, and the behaviour under flow (rheological properties). The rheology is important during and after processing. The pumping behaviour, filling of packs, and texture during pouring, spooning and chewing all depend critically on the relative movement of the droplets past each other.

Although emulsions are defined as liquid/liquid systems, in many foods the fat phase is partly or wholly crystalline, which has dramatic effects on the stability and properties of the systems. For example, the whipping characteristics of cream are improved by forming the foam at low temperature, as the presence of some solid fat in the droplets enhances the stability of the air bubbles. Butter and margarine also contain crystallised fat, in the external, continuous phase, which acts as a solid matrix to reduce the movement of the water droplets and provide the required texture.

The droplet structure of emulsions also determines the rate of release of flavour in the mouth, and the release of lipid-soluble nutrients into the GI tract. The presence of oil and aqueous phases allows partitioning of ingredients or solutes such as oxygen between the droplets and surrounding liquid, which is a major factor in the release mechanism as well as controlling the environment for microbial growth in the emulsion[2].

3. EMULSION FORMATION

With the exception of fresh milk, food emulsions are prepared by breaking up the dispersed phase liquid into small droplets, a process know as homogenisation. Since the properties of the emulsion are highly dependent on the droplet size distribution, the homogenisation process is critical to the performance. There are a number of ways to form the emulsions, and the most suitable method for a given application depends on the throughput required, the degree of emulsification (droplet size) and the viscosity of the liquids[7]. For most applications requiring droplets smaller than a few microns, the ingredients are mixed together to form a coarse pre-emulsion before the main homogenisation process. This ensures the dispersion entering the homogeniser is of uniform composition, with large droplets that form a starting condition for the main disruption process.

In the food industry, the most common type of homogeniser is the high-pressure valve homogeniser, shown schematically in Figure 1. The crude pre-emulsion is introduced into the input chamber under high pressure. When the pressure exceeds a certain pre-set value, a valve at the end of the chamber opens to form an annular slit through which the emulsion is forced. The slit width is typically 15- 300μm, and the pressure drop across the slit is in the range 3-20 MPa[7]. The passage through the slit and into the second chamber results in a reduction in droplet size, down to 0.1μm. There is some debate as the whether the primary disruption occurs in the laminar flow of the droplets through the slit (at speeds up to 1000m/s) or in the highly turbulent flow field in the second chamber[7,8]. A single passage through the homogeniser often results in a broad distribution of droplet sizes, so the emulsion is commonly subjected to two or more such processes. The process is energy intensive, with the interfacial energy of the new droplets representing less than 0.1% of the input energy. This is a consequence of the dissipative losses from generating such high fluid velocities in the valve. Unless actively cooled, the homogenisation process causes a temperature rise in the emulsion of up to 30ºC. The valve homogeniser is not suitable for very viscous emulsions, as these would require very high pressure with consequent increases in energy input and temperature rise.
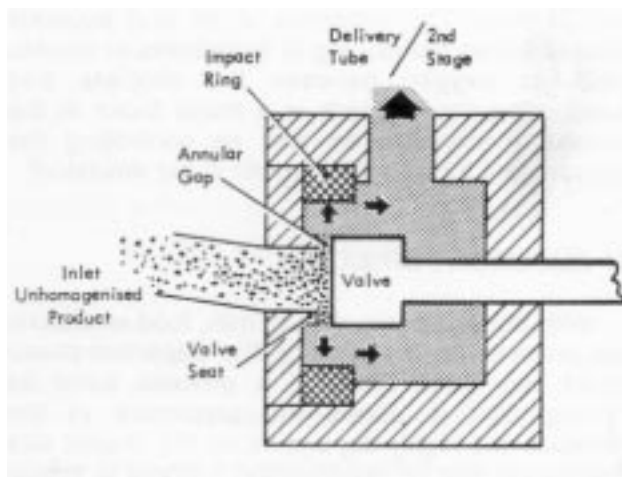
Figure 1
Operating principle of a single-stage high-pressure valve
homogeniser. Reproduced by kind permission of APV Ltd,
Crawley, England

High speed blenders or mixers are also commonly used in the food industry to homogenise emulsions. They are suitable for emulsions of low to medium viscosity with target droplet size larger than 1 μm. For many purposes this is adequate, and the mixing time can be adjusted until the minimum droplet size is attained.

In very viscous systems, the colloid mill is the best homogenisation treatment. Here the crude emulsion is passed through a funnel-shaped gap between static and rotating cones. The high shear stresses generated by the relative movement of up to 20,000 rpm in the gap of typically 50-1000 μm causes the droplets to be broken into a final diameter of a few μm. The process generates considerable heat, and is only routinely used for paste-like dispersions such as peanut butter.

Ultrasonic waves can be used to homogenise emulsions, whether by creating a high shear field near the tip of a vibrating horn, or by projecting a jet of premixed oil and water onto a vibrating blade. Very small droplets can be produced this way, and continuous processing using the blade method is gaining popularity for low viscosity emulsions in the food industry[5].

Whichever process is used to produce emulsions, the same physical factors are important in determining the final droplet size distribution. Ideally, extensional flow would stretch the droplets until the cylinder formed breaks into smaller fragments, but in practice shear flows are found, whether laminar or turbulent. Subjecting an isolated droplet to shear causes both rotation and deformation. The amount of break-up depends on the viscosity of the droplets compared with the

continuous phase (the lower the better); the interfacial energy; initial diameter of the droplet; and the magnitude of the shear field. The presence of the emulsifier helps to reduce the interfacial energy, but can have a counter effect on the ease of break-up due to increased interfacial viscosity. Small-molecule emulsifiers are effective in the break-up process as they adsorb rapidly to the interface, maintaining a low interfacial tension during deformation. However, when there are many droplets present, as in most real systems, the reduction in droplet size is hampered by re-coalescence of the new droplets. For good size reduction, adsorption of the emulsifier to the new interface must occur more rapidly than the inter-droplet collisions. The smallest droplets are thus formed in dilute emulsions with reduced encounter rate, in an excess of rapidly diffusing emulsifier. However, for long term stability, there may be a requirement for an emulsifier with forms a highly viscous skin at the interface, so the choice of ingredients reflects a compromise between the initial droplet size and subsequent properties.

4. CHARACTERISATION OF EMULSIONS

The droplet size is the most important aspect of emulsion structure. However it is not always straightforward to measure, although there are a number of techniques that can be used. The most direct method, microscopy, is useful for qualitative examination of fairly large emulsion droplets (>3μm) within the optical range[9]. Detailed size distributions require a large number of droplets to be imaged, particularly if there is a high level of polydispersity. Electron microscopy can be applied to smaller droplets, with similar drawbacks for quantitative work, and with the added disadvantage of a complex and intrusive preparation procedure. However, it is useful to inspect examine all emulsions initially using an optical microscope, in order to detect aggregation (clumping) and as a verification of the range of sizes present in order to set the conditions for an instrumental determination.

The simplest instrumental determination of droplet size is to measure the turbidity of the diluted emulsion[10]. This technique has traditionally been used in the dairy industry, where the optical properties of the milk-fat droplets are well characterized, and the mean size after homogenization is all that is required.

However, manufactured food emulsions often contain a very wide range of particle sizes and the full distribution is required. The optimum instrument depends heavily on the specific sizes required. For comparatively narrow distributions, containing

particles above 0.3 µm and which are robust to immersion in electrolyte, there is no substitute for the electric sensing zone methods, providing direct counting of particles classified by volume. In this technique, the droplets are diluted in a weak electrolyte, and passed singly through an orifice between two electrodes. The contrast in dielectric properties between the droplet and electrolyte generates a voltage across the electrodes, whose integrated value is related to the volume of the droplet[11].

If the distribution is broader, then variable angle light scattering techniques are useful. Figure 2 shows the principle of operation of a commercial instrument, sutiable for droplets in the range 0.1-1000 µm. In this technique the droplets are diluted to a low optical density, and placed in a laser beam so that the angular distribution of scattered light reflects the distribution of droplet sizes in the beam. The extraction of diameter data from the scattered light pattern requires an optical model, based on the refractive index and absorbance of the droplets[12]. Sometimes it is not easy to obtain these parameters, and calibration experiments are needed, where the droplet sizes have been measured accurately by another technique. Some commercial instruments claim a lower limit of 0.05 µm, but the small particle fractions are difficult to characterize accurately in a broad distribution.

The disc centrifuge is a method favoured in the past by the food industry[11]. The samples are enclosed in a disc-shaped cavity, which is spun about its axis. The concentration of droplets passing a fixed diameter on the disc is monitored. The speed of droplets in the centrifugal field is related to their hydrodynamic diameters, using Stokes' Law (see below), which also requires the droplet density and continuous phase viscosity. The detection device is usually an optical photocell that measures turbidity, requiring further analysis to yield droplet concentration as a function of time. Variants of the method employ detectors based on x-ray or ultrasonic propagation[13].

The techniques listed so far have all required the use of very dilute samples. If the emulsion is changed by the dilution process, the droplets need to be characterized at high concentrations. Confocal optical microscopy enables examination of concentrated emulsions to a depth of a few diameters, but is not suitable for routine sizing[14]. Although opaque to light, concentrated emulsions allow propagation of x-rays and ultrasound, and both have been used as detectors in gravitational or centrifugal sedimentation methods. The attenuation of ultrasound by an emulsion is sensitive to the droplet sizes present, and recently there has appeared on the market an instrument employing this method for particle sizing purposes[15]. NMR techniques are also useful, particularly where the continuous phase is non-aqueous and/or solid as in water-in-oil spreads[16]. The principle of the method is that the diffusion of molecules within droplets is inhibited by the presence of the droplet surfaces, and analysis of the average long-time diffusion rate gives the ratio of droplet surface area to volume.

5. EMULSION STABILITY

Although chemical degradation and microbial growth can both occur in emulsions, the effective shelf-life is frequently limited by physical instability. Figure 3 shows the ways in which an emulsion can change during storage. The mechanisms can be categorised by whether or not the droplets retain their original size, as in creaming and flocculation (aggregation); or swell, merge or disappear as in ripening, coalescence and breaking. The presence of minor components, such as emulsifiers and stabilisers, is important in determining the type of instability and how fast the process occurs.

Creaming or sedimentation of emulsion droplets is caused by the density difference between the droplets and the continuous phase. If the droplets are of oil, they generally rise (creaming), whereas in a water-in-oil emulsion the droplets are denser than the oil phase and tend to sink under the action of gravity. If droplets are very small, typically less than 1 µm in diameter, they diffuse comparatively quickly,
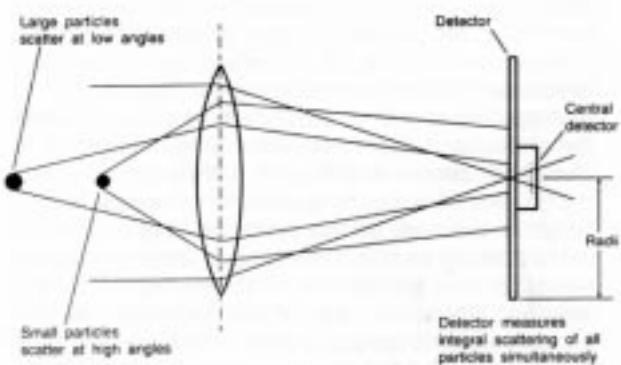

Figure 2
The principle of the variable angle light scattering technique to measure droplet size distribution in emulsions. A laser beam is directed at the dilute dispersion of droplets, and the scattered light is collected by a lens for projection onto a series of semi-circular detectors. The radial position of the light scattered by a droplet is related to its diameter. Reproduced by kind permission of Malvern Instruments, Malvern, England. © Malvern Instruments 1999
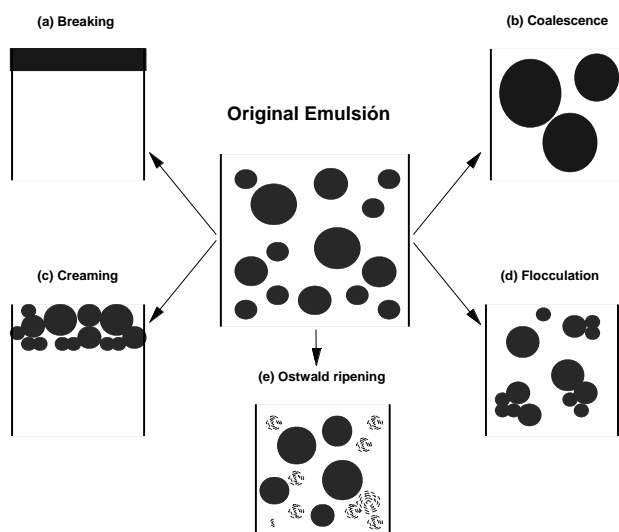
Figure 3
Emulsion instability mechanisms. a) Breaking: complete separa-
tion of oil and water phases. b) Coalescence: the combination of
two droplets to make a large one with the same total volume. c)
Creaming: the movement of oil droplets to the top of the container
due to gravity. d) Flocculation: reversible aggregation of droplets.
e) Ostwald ripening: molecular diffusion of dispersed phase from
smaller to larger droplets

and any vertical movement due to gravity is counteracted by a diffusive remixing against the embryonic concentration gradient. Many food emulsions contain primary droplets larger than 1μm, or are aggregated into effectively larger units, and therefore have a tendency to cream or sediment. The rate V_s of creaming/sedimentation of an isolated droplet of diameter d is governed by Stokes' Law:

$$V_s = \frac{\Delta\rho.g.d^2}{18\eta} \qquad (1)$$

where $\Delta\rho$ is the density difference between the droplets and continuous phase, g is the acceleration due to gravity and η the viscosity of the continuous phase. Droplets of vegetable oil of 2μm diameter, dispersed at low concentration in water, cream to the top of the container at a rate of 17 mm/day. This would rapidly lead to unsightly appearance in a product. In practice there are several ways in which food emulsions are stabilised to creaming. The first is to have such a high concentration of droplets that they are effectively close-packed and the gravitational forces are balanced by repulsive forces

generated when two emulsifier-coated droplets are forced into close contact. This is the mechanism that prevents creaming in traditional mayonnaise, containing >70%v/v oil droplets. However, in many foods it is not desirable to include oil at such high concentrations, and another strategy is to incorporate thickening ingredients into the continuous phase, to increase the value of η in Equation 1. If the added ingredient is a gelling polymer, the presence of an effective yield stress can support the droplets. Where a non-gelling polymer is added, the continuous phase remains liquid-like, but may cause the droplets to form aggregates. Small, individual aggregates generally cream faster than individual droplets because although they incorporate continuous phase and reduce $\Delta\rho$, they effectively increase the value of d in Equation 1. However, above certain critical values of droplet and polymer concentrations, the aggregates form an extended network throughout the container, and creaming is hindered. Such systems often display good creaming stability for a period, which may be months, before catastrophic collapse[17]. This phenomenon is very common in food emulsions, but the underlying mechanisms are not yet understood[18].

Creaming and sedimentation are observed visually when the droplets are of narrow size distribution or moving in large aggregates. In a polydisperse emulsion of individual droplets or small aggregates, a considerable amount of droplet movement can occur before it is visible to the eye. There are several instruments to detect the onset of creaming, based on measurements of droplet concentration at selected heights or as a continuous scan. The detectors may be based on optical transmission or reflection, suitable mainly for dilute emulsions, or the propagation of an ultrasonic wave through the emulsion. In the latter example, shown schematically in Figure 4, the propagation speed of an ultrasonic pulse through the emulsion is determined at a range of heights[19]. Usually a simple relationship exists between the speed and the concentration of droplets at the height measured, so the scan provides a detailed concentration profile. Creaming is detected by the evolution of a gradient in oil concentration during storage. The advantage of this technique is that ultrasound propagates readily through most food dispersions, and the accumulation of concentration profiles over a period of time allows the size distribution of the creaming droplets or aggregates to be estimated.

Thus creaming behaviour can also reveal aggregation or flocculation instabilities. If the aggregates are stable to dilution, they can be detected using particle sizing, or microscopy. There is also a purpose-built instrument available, using an optical technique applied to a dilute emulsion
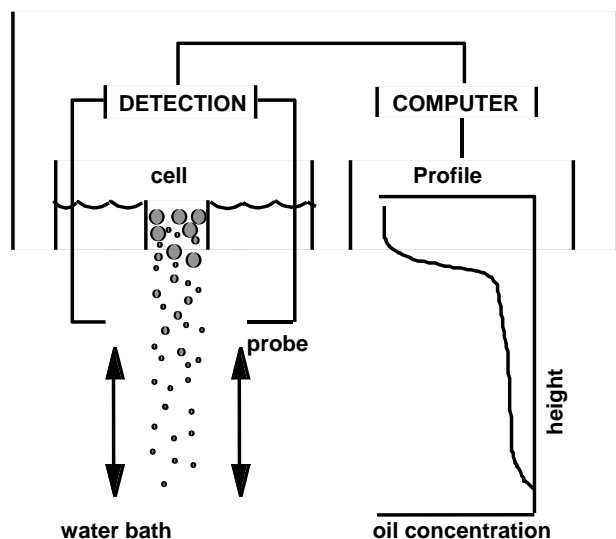
Figure 4
The ultrasonic creaming monitor. The graph shows
schematically the concentration-height profile of oil in an
emulsion during creaming

flowing through a transparent pipe[20]. In this method, the fluctuations of light intensity due to droplets passing through a beam are recorded, and the ratio of the root-mean-square value to the time-averaged mean gives the number and scattering cross-section of the particles. More recently, there have been developments in the use of ultrasonic spectroscopy to characterise flocculation in emulsions, which has the advantage of being suitable for weak aggregates in an undiluted sample[21].

The coalescence of two emulsion droplets into a single large droplet occurs when both long-and short-range inter-particle repulsive forces are too weak to counteract the attractive van-der-Waals forces between the two droplets. Long-range repulsions prevent close encounter, and stabilise against flocculation. These are often generated by the presence of a significant surface charge on the droplets, causing electrostatic repulsion between two droplets of similar charge. However, if a chance encounter of high energy allows closer contact, then short-range forces are important, which are critically dependent on the layer of emulsifier on the droplet surfaces. When two droplets approach closely the emulsifiers effectively form an interfacial membrane between the bulk liquids in the droplets. The physical robustness of the membrane is the only remaining defence against coalescence. Robustness is gained by one of two mechanisms. The first, relevant to small molecule surfactants, is

to form a highly mobile interfacial layer which resists rupture by a rapid response to any thinning of the film. Thinning may occur due to a thermal fluctuation, displacement of the molecules by a more surface-active moiety, or by chemical degradation. If the emulsifier is a good stabiliser, the formation of a local concentration gradient in the membrane stimulates the diffusion of emulsifier to the thinned region, bringing with it some continuous phase molecules (the Gibbs-Marangoni effect[22]). The combination allows the film to thicken once more to a stable width. In the second mechanism, relevant to proteins and other molecules that form a two-dimensional gel-like layer at the interfaces, the mechanical strength of the film provides a barrier to rupture.

Coalescence is monitored by measuring the changes in droplet size distribution. Studies of thin film drainage, mobility and rheology can also give insights into the mechanisms of coalescence stability. Coalescence is a step that must occur before the emulsion breaks entirely, i.e. separates into oil and water component phases. Sometimes food emulsions display a thin layer of bulk oil on their surface that is a consequence of instability to coalescence.

The ripening of emulsion droplets is a second instability that affects primary droplet size. It occurs when the dispersed phase is sparingly soluble in the continuous phase, or when there is a large excess of small emulsifier molecules present as micelles. The ripening only occurs if there is significant polydispersity of droplet size, as it is driven by the higher internal pressure of small droplets compared with large ones. If this driving force is large enough, and there is a transport mechanism for molecules of dispersed phase to move through the continuous phase, then large droplets will grow at the expense of small ones. The transport occurs by means of a slight mutual solubility of the two liquids, or by the action of emulsifier micelles that can solubilise small amounts of dispersed phase. Although it is unusual for emulsions of animal or vegetable oil to undergo ripening, the effect is common in flavour emulsions that contain essential oils such as limonene. An effective way to stabilise against ripening is to incorporate a small concentration of a material in the droplets that is very insoluble in the continuous phase[23]. The chemical potential difference that develops between droplets after a small amount of ripening effectively prevents further size changes. The presence of ripening can be distinguished from a coalescence process by measuring the total number of droplets in the emulsion during storage. In coalescence, this number decreases steadily, but in ripening it changes only when the smallest droplets become too small to detect.

6. FUNCTIONAL PROPERTIES OF EMULSIONS

Emulsion products are generally required to possess characteristic properties of texture, flavour and appearance. All these properties depend on the droplet size distribution, and thus on the bulk stability.

The texture of emulsions is commonly measured using rheological techniques. Although there is debate on the best conditions to mimic the mouthfeel of the products, there is general agreement that physical measurements provide a scientific basis for modification of the flow properties. Very firm, solid-like emulsions such as gelled dairy products are characterised using compression or penetrometer techniques, but most food emulsions are amenable to flow viscometry or oscillatory rheology using commercial rheometers.

Emulsions that are essentially liquid-like are characterised using flow viscometry. In this test, the sample is made to flow at a constant strain-rate, or under a constant shear stress. Dilute emulsions where the droplets are stable and individual (unaggregated) exhibit Newtonian behaviour i.e. the measured viscosity (ratio of shear stress to strain rate) is independent of the shear rate or stress applied. In this situation the unique viscosity obtained is directly related to the viscosity of the continuous phase alone, and displays a linear increase with the concentration of droplets[24]. Clearly, if the continuous phase displays shear-thinning behaviour, as occurs with some polymer solutions, the emulsion also displays non-Newtonian behaviour.

At higher concentrations the droplets contribute more strongly to the emulsion rheology, until a critical concentration is reached, which corresponds to close-packed droplets. The viscosity is theoretically infinite at this concentration (>64% v/v, increasing with polydispersity), but deformation of the liquid droplets prevents full jamming of the particles. The flow behaviour is also strongly dependent on the applied shear rate or shear stress, and the detailed droplet size distribution is important. In general, polydispersity helps to «lubricate» the emulsion, resulting in lower viscosity for a given droplet concentration than in the mono-disperse case.

In emulsions where the droplets are aggregated, which is common in food emulsions containing polymer stabilisers, the rheological behaviour is very complex. For very dilute, aggregated emulsions at low shear rates the aggregates move as individual, but large, particles, and the behaviour is essentially Newtonian. The effect of concentration is more marked than in the unaggregated case because the aggregates trap continuous phase and thus occupy a larger volume than the individual droplets. At high shear rates, the aggregates may become disrupted and the behaviour of the emulsion reverts to that of the same concentration of individual droplets, with consequently reduced viscosity.

In more concentrated aggregated emulsions the behaviour is more complicated. If the aggregates are loosely-packed, a comparatively low concentration of droplets can form a space-spanning network, with distinctive properties. The network has some solid-like properties, exhibiting viscoelasticity in its flow behaviour. This means that under very low strains the network can store energy elastically, and the strain is recoverable. At higher strains the droplets undergo flow, and the behaviour becomes more viscous, with a linear relationship between stress and shear rate. In many cases it is the low strain behaviour that is important in characterising a product, and flow viscometry is not suitable for viscoelastic materials. Instead, oscillatory rheology is used, which entails subjecting a sample to sinusoidal shear at a constant frequency and amplitude. The response of the material is also sinusoidal, but it displays a phase lag between the application of the stress and the resulting strain. In purely elastic materials the strain is in phase with an applied stress, but in purely viscous systems it is the strain rate that is in phase, and the strain lags by a quarter cycle (90°). The response of aggregated emulsions to sinusoidal stress as a function of applied frequency and amplitude is highly characteristic and reveals considerable structural information[25]. In general, emulsions oscillated at low amplitude or high frequency demonstrate elastic (solid-like) behaviour, and at higher amplitude or lower frequency the droplets flow irreversibly and the emulsion behaves more like a viscous liquid.

The flavour of an emulsion arises from ingredients in both the dispersed and continuous phases[26]. If the flavour components contained in the droplets are to be perceived during consumption, they must be released from the droplet structure in the mouth[27]. This is a highly complex area, involving an understanding of the partitioning of flavour components between oil and water phases, and the response to changes in environment due to chewing and dilution with saliva. The majority of perceived flavour is actually sensed by the nose, so an important aspect is the volatility of the compounds, both in the package and during eating. Clearly the interfacial area between the droplet and continuous phases is a controlling factor in the partitioning of flavour compounds between phases, so the droplet size distribution is a key factor.

Similarly, there are a number of factors in the visual appearance of a food emulsion. In many cases the requirement is for opacity, which demands that the structural elements scattering light (usually individual droplets) have diameters in

the range 0.5-5µm. This provides maximum turbidity at a given droplet concentration, but clearly there is a large effect of the number of droplets and the optical properties of the dispersed and continuous phases[28]. Vegetable oil and water have a refractive index difference of typically 0.1, and this allows considerable scattering from oil droplets in the appropriate size range. However, if the aqueous phase of an emulsion contains a high concentration of water-soluble ingredients (e.g. >40% sucrose) then the refractive index difference becomes much smaller, and even a concentrated emulsion may lose opacity. This can be used to advantage in the scientific investigate of emulsions, enabling optical or infra-red techniques to be applied to refractive-index matched systems in order to gain structural information on the components.

7. CONCLUSIONS

This review has sought to introduce the reader to the basic physical issues of emulsion science. To incorporate the required properties of processability, stability, texture, flavour and colour in an emulsion product requires knowledge of far more than the basic functional ingredients. The whole field of colloid science, and the role of interfaces in food systems, is a vast area, requiring detailed understanding of the systems at the molecular, microstructural and bulk length scales.

There are a currently a number of exciting issues in food emulsion science. In some areas the scientist is only now developing an understanding of the important parameters, to explain the phenomenological experience of food formulators. A key current issue is the development of products with reduced fat contents, but with a creamy appearance, texture and flavour[29]. Similarly, the food manufacturer is increasingly required to source ingredients from a wide range of materials and countries, and therefore needs a framework to examine the robustness of the products to modified formulations. The development of new processes, such as high-pressure processing, is also a driving force for a better understanding of the make-up of emulsified foods.

The consumer is increasingly demanding variety in food products, and there are also major issues of food safety in emulsified foods. Recent research on the interactions between the structure of foods and the growth of food-borne pathogens is stimulating multidisciplinary approaches to food safety[30]. Similarly, work on the release of nutrients from complex food matrices is demonstrating the need to develop full understanding of the behaviour of emulsified products in the GI tract, in order to establish the best routes for micronutrient delivery[31].

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