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Review

Crystal stabilization of edible oil foams

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ABSTRACT

Background: Research on non-aqueous, edible foams is scarce compared to aqueous foams. Only recently, edible-gas-in-oil systems stabilized with crystals are being studied because of their omnipresence in food products, but both fundamental and applied studies are still needed.

Scope and approach: This review aims to provide insights into this new promising area in food science, hereby focusing on the Pickering stabilization by crystal particles and the influence of processing on crystal properties. The potential benefits and latest developments of edible oil foams are also discussed.

Key findings and conclusions: Edible oil foams are currently prepared by heating a solution containing a high-melting component in a vegetable oil, cooling this solution to form an oleogel and subsequently whipping it to obtain an air-in-oil system with a high stability to drainage, coalescence and disproportionation. Oil foams provide new opportunities for food technologists to develop unique texturized food products with a reduced fat content and less saturated fat. In addition, these systems can allow food companies to anticipate important trends like sustainability and clean label.

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1. Introduction

Foams are complex colloidal systems with gas bubbles dispersed in a continuous phase containing surface-active agents (Schramm, 2006b). They are widely applied in food industry, personal care products, firefighting, petroleum industry and others (Briggs, 1996; Broze, 1999; Schramm, 1994). This broad application potential gave rise to an increased interest in fundamental and applied research on solid and liquid foams (Bikerman, 2013; Exerowa & Kruglyakov, 1998; Prud'homme, 1995; Schramm, 2006b; Sheludko, 1967; Stevenson, 2012). Liquid foams can be classified into aqueous and non-aqueous foams, depending on the continuous phase.

All foams are thermodynamically unstable due to their high surface area and thus high free energy (Dickinson, 2010). In aqueous foams, low-molecular weight surfactants, amphiphilic polymers, proteins or dispersed particles are introduced to lower the interfacial energy and stabilize the system (Bezulgues, Serieye, Crosset-Perrotin, & Leser, 2008; Hunter, Pugh, Franks, & Jameson, 2008; Patino, Delgado, & Fernández, 1995; Whitehurst, 2008). Foam stabilization by means of solid particles, *i.e.* Pickering

stabilization, gained increased interest because of the ability to produce highly stable aqueous foams. Particles attached to interfaces show a high energy of attachment compared to surfactant molecules, so once adsorbed, they can be considered irreversibly anchored¹ (Binks, 2002). The use of solid particles therefore results in less Ostwald ripening and bubble coalescence and thus an enhanced stability (Hunter et al., 2008). However, particles used to stabilize food foams should be food-grade and therefore, the options are more limited (Lam, Velikov, & Velev, 2014). Recent examples are microparticles from hydrophobic cellulose and colloidal ethyl cellulose (Jin et al., 2012; Wege, Kim, Paunov, Zhong, & Velev, 2008), semi-crystalline fat droplets (Lam et al., 2014) and in case of non-aqueous foams, crystallizing surfactants (Brun, Delamplé, Harte, Lecomte, & Leal-Calderon, 2015; Gunes et al., 2017).

Research on non-aqueous foams is quite limited compared to aqueous foams, especially for edible applications. Only recently, edible-gas-in-oil systems stabilized by particles are being studied as a result of the commercial importance of these structures and their omnipresence in edible systems (Campbell & Mougeot, 1999; Friberg, 2010). Early work by Ross and Nishioka (1977) on non-

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E-mail address: Robbe.Heymans@UGent.be (R. Heymans).¹ Taking into account that under certain conditions, such as processes in which high mechanical forces are present, particles could be driven off the surface.

edible foams suggested that the foamability of the system generally increased when the system was close to a phase separation boundary. Similar conclusions were drawn by [Binks, Davies, Fletcher, and Sharp \(2010\)](#) for additives used in lubricating oils and by [Friberg, Wohn, Greene, and Van Gilder \(1984\)](#) for xylene foams stabilized by triethanolammonium oleate surfactants. Shrestha and others researched oil foams composed of olive oil, liquid paraffin, squalene and mono- and diglycerol fatty acid esters. Both solid and liquid crystal particles were found to reduce the surface tension of the oil-air interface ([Shrestha, Shrestha, Sharma, & Aramaki, 2008](#); [Shrestha, Shrestha, Solans, Gonzalez, & Aramaki, 2010](#)). Extensive studies on air-oil mixtures stabilized by particles were conducted by [Murakami and Bismarck \(2010\)](#) using tetrafluoroethylene particles and [Binks and Rocher \(2010\)](#) and [Binks, Rocher, and Kirkland \(2011\)](#) using a range of fluorinated particles. Subsequent work identified the conditions required for making stable oil foams in terms of the extent of fluorination of the particles and the oil surface tension ([Binks & Tyowua, 2013](#); [Binks, Sekine, & Tyowua, 2014, 2015](#)). Uniquely, [Bergeron, Hanssen, and Shoghl \(1997\)](#) did not use a Pickering stabilization but applied a surfactant adsorption strategy. Fluorocarbons with low surface energy were capable of lowering the dodecane-air tension.

Only recently, the approach of Pickering stabilization of the air-oil interface was successfully applied on edible model systems by [Brun et al. \(2015\)](#), [Fameau et al. \(2015\)](#), [Binks, Garvey, and Vieira \(2016\)](#), [Mishima, Suzuki, Sato, and Ueno \(2016\)](#) and [Gunes et al. \(2017\)](#). Fundamental and applied knowledge of these edible oil foams is crucial since they are found in a variety of food products like aerated chocolate bars and cake. Moreover, these systems have an enormous potential in reformulating food products with reduced caloric content and are popular in the discipline of gastronomy due to their unique texture and mouthfeel ([Binks et al., 2016](#); [Friberg, 2010](#); [Haedelt, Beckett, & Niranjana, 2007](#); [This, 2002](#); [Wilderjans, Luyts, Brijns, & Delcour, 2013](#)).

Edible oil foams have an enormous un-tapped potential, and research in this area is therefore rapidly advancing. [Fig. 1](#) illustrates the expanding number of citations of articles which were searched as 'oil foam' as the topic and selecting the Food Science Technology category from the Web of Science Core Collection. This review aims to provide insights into this new promising area in food science, hereby focusing on the Pickering stabilization by crystal particles, the influence of processing on crystal properties and possible

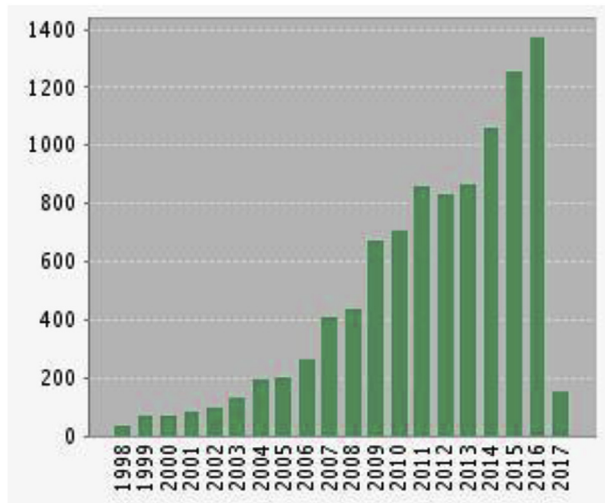


Fig. 1. Citations in Each Year given by the search term 'oil foam' in Food Science Technology ([Web Of Science, 2017](#)).

applications. Conclusions from oil foam research have been given throughout the entire manuscript and where relevant, also aqueous foams were discussed. However, one has to bear in mind that each study applies a specific production protocol, which strongly affects the foam properties (e.g. overrun, air bubble size, etc.). One therefore has to be critical when extrapolating these results to other research.

2. Basic energy aspects and (de)stabilization of Pickering (oil) foams

Pure liquids cannot foam unless surface active material is present ([Pugh, 1996](#)). Low molar mass surfactants and surface-active polymers are therefore used to slow down the destabilization kinetics of the foams to ensure their (meta)stability during application ([Nielloud, 2000](#)). The recent attention for particle stabilized foams results from the success of Pickering emulsions ([Chevalier & Bolzinger, 2013](#); [Gao et al., 2014](#); [Pickering, 1907](#); [Ramsden, 1903](#)). Pickering emulsions were first described by [Pickering \(1907\)](#) and [Ramsden \(1903\)](#) and a decade of research on these systems has proven their relevance for food systems. Emulsion research can partly be extrapolated to foam systems, although there are less potential candidates for foam stabilization due to the larger density differences between air-liquid phases, the increased effect of disproportionation and the ability of hydrophobic particles to act as foam de-stabilizers ([Hunter et al., 2008](#)). As a result, the size and contact angle range are more limited for foams than for emulsions ([Hunter et al., 2008](#); [Lam et al., 2014](#)).

2.1. Solid particles versus surfactant molecules

Solid particles act in many ways similar to surfactant molecules. The concept of the hydrophilic-lipophilic balance, introduced by [Griffin](#), is one of the most important theories in determining whether a surfactant will stabilize an oil or water continuous system ([Griffin, 1946](#)). In the case of particles, the particle wettability, expressed by the contact angle (θ), is the parameter determining the phase in which they will preferentially reside. [Schramm \(2006a\)](#) defined the contact angle as 'the angle, measured through the liquid, that is formed at the junction of three phases'. In general, hydrophilic particles (e.g. metal oxides) with a contact angle smaller than 90° measured through the water phase, stabilize water continuous systems (aqueous foams and O/W emulsions), while the opposite is true for hydrophobic particles (e.g. hydrophobic silica), which stabilize oil continuous systems (W/O emulsions) ([Binks, 2002](#); [Kaptay, 2006](#); [Midmore, 1999](#)). Similarly, oil foams will be stabilized by particles with a contact angle measured through the oil phase lower than 90° ([Binks et al., 2011](#)). For more complex configurations like double layers of particles, different stabilizing contact angles can be found ([Kaptay, 2006](#)). Another difference between particles and surfactant molecules is the adsorption kinetics. Under diffusion-controlled conditions, the particle adsorption shows slower kinetics because of their large size compared to that of surfactant molecules which are in rapid and dynamic equilibrium between the interface and the bulk phase ([Binks, 2002](#)). However, once attached, particles will increase the stabilization because of their higher detachment energy and maximum capillary pressure ([Hunter et al., 2008](#)).

2.2. Particle detachment energy

The energy of detachment of a particle from an interface relates the particle properties (contact angle and size) and the initial air-liquid tension to the stabilization of the foam. The detachment energy is related to the free energy involved in removing an

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