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Transport and release in nano-carriers for food applications

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ABSTRACT

Encapsulation of active compounds such as nutraceuticals or preservatives increases their concentration, bioavailability and stability in food products. Nanoparticle carriers are an effective encapsulation method that provides protection from environmental degradation agents and control over the rate of compound release. This review focuses on the parameters affecting transport in a number of nanoparticle types used in (or with the potential for) food and beverage applications: Emulsions and Pickering emulsions, solid lipid nanoparticles (SLN), nanostructured lipid carriers (NLC), liposomes, and colloidosomes. Emphasis is placed on the effect of medium conditions, nanoparticle structure and size, and the role of the shell.

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1. Introduction

The nutritional value of foods and beverages can be enhanced by incorporation of vitamins and 'nutraceuticals' (Braithwaite et al., 2014; Walker et al., 2015). The concentration and bioavailability of flavor, scent or color agents affect sensory reactions to foods (Berton-Carabin and Schroen, 2015; Braithwaite et al., 2014; Dickinson and Leser, 2007; Gibbs et al., 1999; Hasenhuettl and Hartel, 2008; McClements, 2013, 2015; McClements et al., 2009; Sagalowicz and Leser, 2010). Antimicrobials and preservatives extends shelf-life (Berton-Carabin and Schroen, 2015; Braithwaite et al., 2014; Dickinson and Leser, 2007; Gibbs et al., 1999; Hasenhuettl and Hartel, 2008; McClements, 2013, 2015; McClements et al., 2009; Sagalowicz and Leser, 2010). However, many of these compounds have low solubility in foodstuffs, or are highly sensitive to environmental degradation agents such as free radicals, pH, and enzymes. Their encapsulation concentrates the active ingredient in a protective environment, that of the carrier's interior (Coupland and Hayes, 2014; McClements, 2013), while also allowing control over the release profile.

Carriers for active ingredients can range in size from several nm to hundreds of microns. However, nanoparticles of order 500 nm or less are preferable for food applications: They do not perturb the optical properties of the suspension significantly, thereby keeping

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the foods' original appearance. Because Brownian motion increases with particle size (Reddy and Fogler, 1981), suspensions containing smaller particles will be more stable against phase separation (creaming or settling). The surface to volume ratio increases with decreasing particle radius, which increases the bio-availability of encapsulated compounds (McClements, 2013).

Nano-carriers come in many varieties. Most are designed to increase the effective solubility of hydrophobic compounds in aqueous-based foods and beverages, or of hydrophilic ones in oil-based systems. Yet, encapsulation of hydrophilic compounds in aqueous solutions (or hydrophobic ones in oil-based solutions) is also of interest, since it enables the shielding of sensitive materials from environmental degradation agents, masks unfavorable flavors or scents of nutrients or preservatives and offers control over the compound release rate (Coupland and Hayes, 2014).

Fig. 1 depicts some of the nanoparticles that are commonly used or studied for encapsulation and release in food-related applications: Hydrophobic compound encapsulation utilizes cores that may be liquid (emulsions and microemulsions), solid (solid lipid nanoparticles-SLNs), or a mix of solid and liquid domains (nano-structured lipid carriers-NLCs). Particles for encapsulation of hydrophilic ones are composed of an aqueous core, delineated from the surrounding continuous phase by a shell. These include nano-hydrogels, liposomes and colloidosomes. In both categories, the nanocarriers are stabilized by either emulsifying molecules (emulsions) or by colloidal particles—CPs (Pickering emulsions).

The properties and synthesis methods of these nanoparticles have been extensively discussed elsewhere, and are outside the scope of this review (Aditya and Ko, 2015; Arditty et al., 2004, 2005; Arnaud, 1997; Attama, 2011; Berton-Carabin and Schroen, 2015; Dan, 2012; Dickinson, 2009, 2010; Imran et al., 2015; Joye and McClements, 2014; Madivala et al., 2009; Maherani et al., 2011; McClements, 2012, 2015; McClements et al., 2009; Muller et al., 2002; Nie et al., 2008; Niu et al., 2010; Patra et al., 2010; Persson et al., 2014; Priest et al., 2011; Rousseau, 2000; Shewan and Stokes, 2013; Shilpi et al., 2007; Torchilin, 2001; Umbanhowar et al., 2000; Weiss et al., 2008; Yan and Pochan, 2010; Yao et al., 2014; Yow and Routh, 2006). This paper focuses on the relationship between the structure of the nanoparticle carrier and transport.

Transport in nanoparticles occurs in three regions: The nanoparticle core, the coating shell, and the surrounding medium. Inside the nanoparticle, transport is driven by concentration gradients that develop between the particle center and the interface with the solution. In the medium, it is set by the concentration gradients between the bulk solution and the nanoparticle interface (although forced mixing may play a role). The shell acts as an intermediary between the two; in some cases, such as the surfactant monolayers stabilizing emulsions, the shell effect is negligible. In others–as in colloidosomes—it may provide a significant barrier to transport.

2. Transport in nano and micro-particles

The rate of transport into or out of nanoparticles is crucial when considering carrier' functions: As noted, one of the main roles of encapsulation is to stabilize and protect the active compound from the environment. Therefore, the flux of environmental degradation agents (free radicals, enzymes) into the particle should be suppressed to maintain compound efficacy. At the same time, leakage of the compounds should be minimized during the storage period (but activated when release is desired). Transport characteristics can also be used to design nanoparticles with a specific release profile: Although many applications require instantaneous release of the active compound when some pre-determined conditions are encountered (e.g., the release of nutraceuticals in the gastro-intestinal system), others may require a slow, continuous release profile over a period of time (for example, flavors).

Transport in the nanoparticle core is dominated by diffusion—driven by the concentration difference between the particle center and the interface with the surrounding medium. Three parameters set the rate of transport inside the nanoparticle: Particle size, the diffusion coefficient of the compound in the core, and the concentration difference between the initial loading and the interface with the surrounding suspension (or the inner side of the shell, if that present a significant barrier).

Studies conducted on hydrogel nanoparticles, where there is no shell to hinder transport, show that the release rate was more rapid from smaller nanoparticles than larger ones (see, for example, (Al-Helw et al., 1998)). The rate varied with the diffusion coefficient of the compound in the nanoparticle, a function of the nanoparticle properties (e.g. hydrogel crosslink density (Jaiswal et al., 2013)) or—in a given type of nanoparticle, the compound itself (Demarchi et al., 2014). The increase in transport rate with decreasing particle

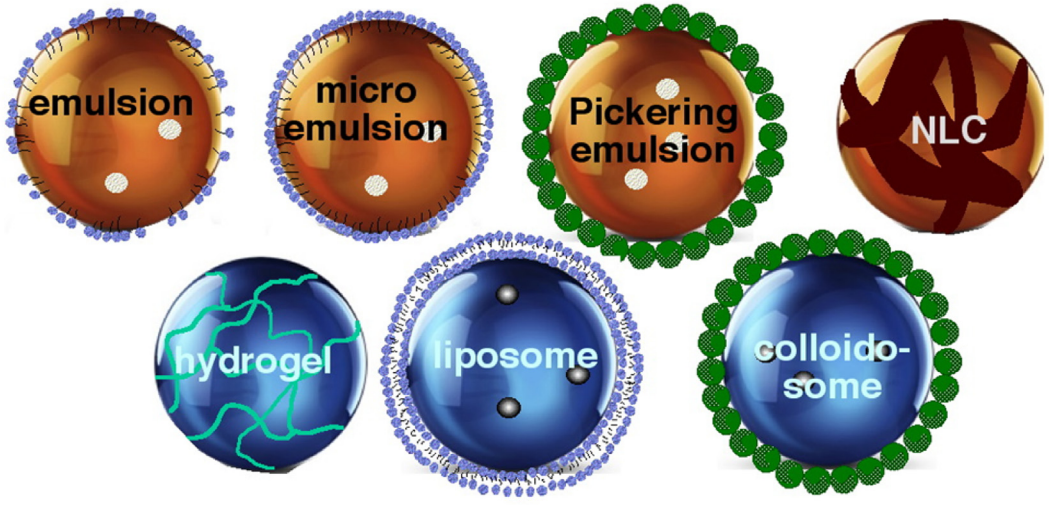

Fig. 1. Nanoparticles for encapsulation of active compounds. Top: Particles with a hydrophobic core. Bottom: Particles for encapsulation of hydrophilic compounds. Blue denotes aqueous medium, light brown a liquid lipid (or oil) phase, and dark brown a solid lipid phase. Green spheres are colloidal particles, and small blue molecules are emulsifiers.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)