Food Hydrocolloids: Application as Functional Ingredients to Control Lipid Digestion and Bioavailability

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Abstract

One of the most popular research areas in food hydrocolloids over the past decade or so has been their application as functional ingredients to modulate the gastrointestinal fate of foods. In particular, they are being utilized to control the hydrolysis of macronutrients (such as fat, protein, and starch) in the gastrointestinal tract, as well as to alter the pharmacokinetics and bioavailability of hydrophobic bioactive agents, including oil-soluble vitamins (*e.g.,* vitamin A, D, E, and K), nutraceuticals (*e.g.,* carotenoids, phytosterols, curcumin, resveratrol, and quercetin) and healthy lipids (*e.g.,* omega-3 fatty acids and conjugated linoleic acids). Food hydrocolloids may be naturally present in foods (such as fruits, vegetables, seeds, and cereals), they may be added as functional ingredients (such as thickening, gelling, emulsifying or stabilizing agents), or used to construct colloidal delivery systems (such as emulsions or microgels). Hydrocolloids can be used to protect bioactive agents from chemical degradation within foods and beverages during storage, but then increase their bioavailability after consumption. Moreover, they can be used to target the delivery of bioactive agents to particular sites in the gastrointestinal tract or to modulate their release profile. Food hydrocolloids are therefore versatile natural ingredients for the formulation of a new generation of functional food products designed to enhance human health and wellbeing. This article provides a review of the application of food hydrocolloids, mainly proteins and polysaccharides, for modulating the gastrointestinal fate of functional foods, with an emphasis on their ability to control macronutrient digestion and bioactive bioavailability.

Keywords: Dietary fiber; delivery systems; nanoemulsions; microgels; gastrointestinal tract; nutraceuticals

1. Introduction

A major trend in the field of food hydrocolloids over the past decade or so has been the use of proteins and polysaccharides as functional ingredients to modulate the gastrointestinal fate of macronutrients, micronutrients, and nutraceuticals, collectively referred to as "nutrients" in the remainder of this article. These hydrocolloids can be used in a variety of ways to achieve this goal. They can be utilized as building blocks to assemble food-grade colloidal delivery systems to encapsulate, protect, and release nutrients (Shewan & Stokes, 2013; Taheri & Jafari, 2019; Zhang, Zhang, Chen, Tong, & McClements, 2015). They can be used as functional ingredients to alter the nature of the gastrointestinal fluids inside the human body (especially their rheological properties) so as to control the mixing, digestion, and transport of nutrients (Foster & Norton, 2009; Pedersen, et al., 2013; Tharakan, Norton, Fryer, & Bakalis, 2010). They can be used to bind nutrients and gastrointestinal constituents (such as bile acids, enzymes, or calcium ions), thereby altering the digestion and/or absorption of the nutrients within the body (Hu, Li, Decker, & McClements, 2010; Zhou, Xia, Zhang, & Yu, 2006). They can be utilized as prebiotics to change the composition of the gut microflora, thereby improving human health (Wang, et al., 2019). Moreover, the presence of hydrocolloids in natural foods, such as fruits, vegetables, cereals, nuts, or seeds, may be utilized for their ability to modulate the gastrointestinal behavior of foods (Singh & Gallier, 2014). The purpose of this manuscript is to provide an overview of some of the recent research on the utilization of food hydrocolloids to create functional foods and beverages designed to enhance human health, wellbeing, or performance. In particular, the key molecular, physicochemical, and functional properties of hydrocolloids suitable for this purpose are highlighted.

2. Food Hydrocolloids

There have been many excellent articles and books published on the molecular characteristics, physicochemical properties, and functional performance of food grade hydrocolloids (Li & Nie, 2016; Phillips & Williams, 2009; Stephen, Phillips, & Williams, 2006), and readers are referred to these publications for more detailed information about specific hydrocolloids. Briefly, the two most important types of functional hydrocolloids

in foods are proteins and polysaccharides (DNA or RNA are rarely used as functional food ingredients). Most food proteins are polymers consisting of a linear chain of amino acids linked together by peptide bonds. The number, type, and sequence of the amino acids determines the molecular weight, conformation, charge, and polarity of the proteins, which in turn impacts their solubility, surface activity, thickening, gelling, foaming, enzyme activity, and nutritional attributes. Some important food proteins have other groups covalent attached to the polypeptide chain, such as casein (phosphates), lactoferrin (sugars), or myoglobin (heme), and hemoglobin (heme), which play a key role in their functionality. Polysaccharides are polymers consisting of monosaccharides linked together by glycosidic bonds. The type, number, sequence, and bonding of the monosaccharides impacts their molecular and functional properties. A number of the most important food hydrocolloids used to modulate the gastrointestinal fate of foods are summarized in Table 1 along with their key molecular and functional attributes.

3. Key Functional Attributes Impacting Gastrointestinal Fate

Food hydrocolloids can modulate the gastrointestinal fate of foods in a variety of ways (Blackwood, Salter, Dettmar, & Chaplin, 2000). In this section, some of the key functional attributes of food hydrocolloids that impact their behavior inside the human gut are briefly discussed.

3.1. Solubility

Food hydrocolloids may be fully soluble, partially soluble, or insoluble in water (or gastrointestinal fluids) depending on their molecular characteristics, particularly their surface hydrophobicity, charge, and molecular weight (Guo, Hu, Wang, & Ai, 2017a). Water solubility tends to decrease with increasing surface hydrophobicity because of the increase in hydrophobic attraction between the non-polar patches on the surfaces of different hydrocolloid molecules. This is the main reason that hydrophobic proteins, such as zein and gliadin, have low water-solubilities (Davidov-Pardo, Joye, & McClements, 2015). The water-solubility may also be low if there are relatively strong hydrogen bonds between linear polysaccharide chains that can come close together, as in cellulose and mannan (Guo, et al., 2017a). The water-solubility of hydrocolloids tends to decrease as their electrical charge decreases because of the reduction in electrostatic repulsion

between them (Curtis & Lue, 2006). This is the reason why many proteins tend to aggregate and precipitate close to their isoelectric points (Gehring, Gigliotti, Tou, Moritz, & Jaczynski, 2010). Conversely, highly charged hydrocolloids may precipitate in the presence of oppositely charged substances due to an electrostatic attraction between, *e.g.,* when an anionic polysaccharide is mixed with a cationic protein (Weiss, Salminen, Moll, & Schmitt, 2019). Hydrocolloid solubility tends to decrease with increasing molecular weight because of the reduction in the entropy of mixing, which favors the random distribution of the hydrocolloids throughout the solvent (Curtis, et al., 2006).

To a first approximation, the solubility of hydrocolloids (especially globular proteins) can be treated theoretically by assuming they are colloidal particles and calculating the various colloidal interactions between them, such as van der Waals, steric, hydrophobic, and electrostatic (Curtis, et al., 2006): if the molecules tend to aggregate they have a low solubility, but if they tend to stay apart they have a high solubility.

The functionality of many hydrocolloids depends on their solubility in the aqueous phase of foods, as well as in the aqueous gastrointestinal fluids. The ability of proteins or polysaccharides to thicken solutions, form gels, or stabilize emulsions often requires that they have a good water-solubility (Phillips, et al., 2009). Thus, hydrocolloids that are used for this purpose, such as gum arabic, modified starch, whey proteins, caseins, and soy proteins should have good water-solubility characteristics (at least under the required solution conditions). Conversely, hydrocolloids that are insoluble in water, such as zein or gliadin, are useful for constructing colloidal particles that can be used as delivery systems in foods (Fathi, Donsi, & McClements, 2018; Tapia-Hernandez, et al., 2019). Insoluble hydrocolloids, such as cellulose or chitin, can also be used to form functional nanoparticles by breaking down bulk materials into smaller fragments using mechanical or chemical methods (Duan, Huang, Lu, & Zhang, 2018; Khalil, et al., 2014). These kinds of organic nanoparticles have been shown to alter the digestibility of macronutrients (such as lipids) using both *in vivo* and *in vitro* studies, which has been linked to various physicochemical and physiological mechanisms (DeLoid, et al., 2018; Liu, Kerr, & Kong, 2019).

3.2. Binding Properties

Food hydrocolloids may contain a number of different functional groups on their

surfaces, including non-polar, polar, anionic, and cationic groups, with the number, type and distribution depending on the molecule involved (Phillips, et al., 2009). As a result, they are able to bind to other molecules in their environment through a variety of molecular interactions (Foegeding & Davis, 2011; Stephen, et al., 2006). For instance, hydrocolloids with accessible non-polar patches on their surfaces can bind non-polar molecules through hydrophobic interactions, whereas those with negatively or positively charged patches can bind cationic or anionic molecules through electrostatic interactions, respectively (Blackwood, et al., 2000). As specific examples, acetylated lupin fibers have been shown to bind bile salts through hydrophobic interactions (Cornfine, Hasenkopf, Eisner, & Schweiggert, 2010), whereas cationic chitosan has been shown to bind anionic bile salts through electrostatic interactions (Thongngam & McClements, 2005).

In general, the binding interactions between two substances ("receptor" and "ligand") can be characterized by a number of parameters: the number of binding sites, the affinity of each binding site, and the molecular origin of the binding interaction (*e.g.,* hydrogen bonding, electrostatic forces, hydrophobic forces, and/or van der Waals interactions). In the case of hydrocolloids with multiple binding sites, the sites may act independently or dependently, may be similar or dissimilar from each other, and may be specific or non-specific. The nature of the binding interactions involved depends on the type and concentration of the receptor and ligand, as well as the prevailing environmental conditions (such as pH, ionic strength, and temperature). Consider a simple binding interaction between a receptor and ligand given by the equation:

$$R + L \leftrightarrow RL \tag{1}$$

Thermodynamic analysis of this interaction leads to the following expression relating the number of bound ligands to the ligand concentration and binding constant (Hulme & Trevethick, 2010):

$$[RL] = \frac{[L][R_T]}{[L]+K_d} \tag{2}$$

Here, [RL] is the concentration of bound ligand, [L] is the concentration of free ligand,

176 [R_T] is the total receptor concentration, and K_d is the equilibrium dissociation
177 constant, which provides a measure of the tendency of the receptor–ligand complex to
178 dissociate. The fraction of the binding sites (F_B) on the receptor that are bound can then
179 be obtained by rearranging this equation:
180
181 $$F_B = \frac{[L]}{[L]+K_d} \quad (3)$$
182
183 This equation allows one to plot the fraction of ligand molecules bound as a function of
184 the free ligand concentration, provided the dissociation constant of the binding site is
185 known. The fraction of binding sites occupied increases with increasing ligand
186 concentration and decreasing dissociation constant (*i.e.,* increasing binding affinity)
187 (**Figure 1**).
188 In practice, binding interactions involving food hydrocolloids and gastrointestinal
189 components are much more complex than this simple receptor-ligand mechanism, and so
190 more complex mathematical models are required. For instance, the hydrocolloid may
191 have multiple binding sites, the conformation of the hydrocolloid may change after
192 binding, or ligands may bind as molecular complexes (like micelles) rather than
193 individual molecules (monomers). Binding interactions involving hydrocolloids can alter
194 the way that foods behave inside the human gut, which may be either detrimental or
195 beneficial to human nutrition as discussed in Section 5.3.2.

196 ## 3.3. Surface Activity and Interfacial Properties

197 A number of important food hydrocolloids are amphiphilic, *i.e.,* they have both non-
198 polar and polar segments on the same molecule, *e.g.,* most proteins, gum arabic, and
199 OSA-modified starch. As a result, they can adsorb to oil-water interfaces and form
200 protective coatings (Dickinson, 2003; Garti & Leser, 2001). These types of hydrocolloids
201 are often used to form and stabilize oil-in-water emulsions, which are commonly used as
202 delivery systems for nutrients (McClements, 2015). Many proteins are surface active
203 molecules that can protect oil droplets from aggregating, including those isolated from
204 animal (egg, milk, and meat) and plant (soy, pea, fava bean, and rice) sources. Most
205 polysaccharides are not very surface activity because they have too many hydrophilic

groups on them, but a few of them exhibit strong surface activity because they have some hydrophobic groups attached to the hydrophilic backbone, such as gum arabic, OSA-modified starch, and beet pectin. The nature of the hydrocolloids used to coat the droplets in oil-in-water emulsions can have a pronounced impact on their gastrointestinal fate, by altering the aggregation state of the oil droplets or by altering their surface characteristics (see Section 5.).

The adsorption of a substance to an interface is often described by the *Langmuir adsorption isotherm* (McClements, Bai, & Chung, 2017):

$$\theta = \frac{\Gamma}{\Gamma_\infty} = \frac{c/c_{1/2}}{1 + c/c_{1/2}} \tag{4}$$

Here, θ is the fraction of adsorption sites actually occupied by the substance, Γ is the amount of the substance adsorbed to the surface, Γ_∞ is the total amount of the substance that could be adsorbed to the surface when it is fully saturated, c is the concentration of the substance in the surrounding solution, and $c_{½}$ is the concentration of the substance in the surrounding solution when θ = ½. The surface activity of a substance can be defined as: $SA = 1/c_{½}$, which provides a quantitative measure of the surface binding affinity. The surface activity of a substance can be related to the free energy of adsorption:

$$K = \frac{1}{c_{1/2}} = \exp\left(-\frac{\Delta G_{ads}}{RT}\right) \tag{5}$$

Here, ΔG_{ads} is the free energy change that occurs when a substance moves from the surrounding fluid to the surface. Thus, the greater (more negative) is the value of ΔG_{ads}, the stronger is the affinity of the substance for the surface. The adsorption free energy is made up of enthalpy and entropy contributions. The *enthalpy contributions* are due to changes in the magnitude of the molecular interactions as a result of adsorption, such as van der Waals, electrostatic, hydrogen bonding, and hydrophobic and steric interactions. The entropy contributions are due to changes in the number of ways the substance can be arranged in the non-adsorbed and adsorbed states, such as the ability to freely change

location, rotate, or undergo conformational changes. In some cases, the various contributions to ΔG_{ads} can be calculated using mathematical models (Norde, 2011).

The adsorption of hydrocolloids to the interfaces in multiphase foods (such as emulsions or starch suspensions) can alter their gastrointestinal fate. These effects depend on the nature of the interfacial layers formed, such as their composition, structure, thickness, charge, and polarity (McClements, et al., 2017). For instance, the interfacial layer properties may impact the aggregation state of fat droplets within the GIT, which would alter the surface area available for digestive enzymes to adsorb to (Zeeb, Lopez-Pena, Weiss, & McClements, 2015). Alternatively, they may form a steric barrier that inhibits the ability of the digestive enzymes to access the macronutrients (McClements & Li, 2010). The potential impact of interfacial layers on the GIT of foods is discussed in a later section (Section 5.3.3).

3.4. Thickening Properties

Some hydrocolloids are highly effective at increasing the shear viscosity of aqueous solutions due to their large molecular dimensions (Bai, et al., 2017). The viscosity of a polymer solution is determined by the fluid flow around the polymer molecules, since this generates additional friction within the fluid (energy dissipation). Thus, hydrocolloids that have highly extended structures tend to be more effective at thickening aqueous solutions because of their ability to perturb the fluid flow more strongly (**Figure 2**). The ability of a hydrocolloid to increase the viscosity of an aqueous solution can be related to its volume ratio (R_V), which is the effective volume occupied by the molecule in solution (polymer chain plus entrained water) divided by the volume occupied by only the polymer chain alone (Bai, et al., 2017). The greater the volume ratio, the more effective is the hydrocolloid at increasing the viscosity. The volume ratio tends to increase with increasing molecular weight, decreasing branching, and increasing extension. Thus, rod-like molecules (like xanthan) have higher viscosities than random coil molecules (like hot gelatin), which in turn have higher viscosities than compact globular proteins (like whey or egg proteins).

A relatively simple semi-empirical equation can be used to predict the ability of food hydrocolloids to thicken aqueous solutions (Bai, et al., 2017):

$$\eta = \eta_1 \left(1 - \frac{\phi_E}{\phi_C}\right)^{-2} \quad (6)$$

In this equation, η is the shear viscosity of the hydrocolloid solution, η_1 is the shear viscosity of the aqueous solution surrounding the hydrocolloids, ϕ_E is the *effective volume fraction* of the hydrocolloid molecules in solution, and ϕ_C is a critical packing fraction ($\approx$ 0.57). This latter term corresponds to the volume fraction of spheres that can be packed into a suspension before they become tightly packed, after which there is a steep rise in the viscosity of the suspension. To a first approximation, the effective volume fraction occupied by hydrocolloid molecules in solution is given by (Bai, et al., 2017):

$$\phi_E = \tfrac{4}{3}\pi r_H^3 \left(\frac{cN_A}{M}\right) \quad (7)$$

In this expression, r_H is the hydrodynamic radius of the hydrocolloids, c is the hydrocolloid concentration, N_A is Avogadro's number, and M is the hydrocolloid molecular weight. As shown in **Figure 3**, these equations predict that the ability of a hydrocolloid to thicken a solution rises as the concentration and effective volume of the hydrocolloid molecules increases.

A simple expression for the critical viscosity concentration (CVC), which is the hydrocolloid concentration where there is a steep rise in viscosity due to overlap of the polymer chains, has been derived from the above equations, which relates the thickening power to the radius of hydration of a hydrocolloid (Grundy, McClements, Ballance, & Wilde, 2018):

$$CVC = 21 \times \frac{M}{r_H^3} \quad (8)$$

Here, CVC is given in wt% when the molecular weight of the hydrocolloid is given in kg mol^{-1} and the radius of hydration is given in nanometers. The thickening power can be conveniently defined as the reciprocal of CVC. Hence, the thickening power increases as the radius of hydration increases (for the same molecular weight), *i.e.,* the hydrocolloid

295 molecules become more extended. Hence, long rigid hydrocolloids (like xanthan gum)
296 are much more effective thickening agents than compact globular hydrocolloids (like
297 whey protein) (Figure 3).
298 Overall, these equations are useful for understanding the potential for different
299 hydrocolloids to thicken aqueous solutions. The ability of hydrocolloids to thicken
300 aqueous solutions can be utilized to control the gastrointestinal fate of foods. For
301 instance, these hydrocolloids can be used to increase the viscosity of the gastrointestinal
302 fluids in the stomach or small intestine, thereby slowing down mixing and mass transfer
303 processes and altering the release of flavors or nutrients (see Section 5.3.1).

304 **3.5. Gelling Properties**

305 Many food hydrocolloids are capable of forming hydrogels consisting of a network
306 of cross-linked biopolymer molecules that entrap water through capillary forces (Phillips,
307 et al., 2009). The nature of the gels formed, such as their rheology, appearance, and
308 response to environmental changes, depend on the type of biopolymers and cross-links
309 employed. Thus, it is possible to form hydrogels with different optical properties (clear,
310 turbid, opaque), rheological properties (soft to hard, rubbery to brittle), setting properties
311 (cold-, hot-, salt-, or enzyme-set), and digestibility (indigestible or digestible). Hydrogels
312 can be formed within a food product prior to consumption or they can be formed within
313 the human body after ingestion of the hydrocolloids (Norton & Frith, 2001). The
314 dimensions, pore size, and degradability of hydrogels can be tuned so as to control the
315 retention, stability, and release of nutrients within the gastrointestinal tract (McClements,
316 2017). Hydrocolloids can be used to form macroscopic or microscopic gels depending on
317 the application. A number of examples of using hydrocolloids for this purpose is given
318 later.
319 The elastic modulus of a polymer gel depends on the nature, concentration, and
320 interactions of the polymer molecules in the gel network (Vilgis, 2015). A variety of
321 mathematical models have been developed to relate the structural properties of polymer
322 gels to their rheological properties (Gabriele, de Cindio, & D'Antona, 2001; Rubinstein,
323 Colby, Dobrynin, & Joanny, 1996). These models predict that the elastic modulus
324 depends on polymer concentration, crosslinking density, and bond strength. In addition,
325 theoretical models have been developed to describe the elastic modulus of polymer gels

containing embedded particles (Fu, Feng, Lauke, & Mai, 2008). These theories show that the size, concentration, and interactions of the colloidal particles with the polymer network impact their rheological properties, such as stiffness, strength and toughness. These models can sometimes be useful for predicting the behavior of food gels before consumption, but they are usually too simple to understand the complex behavior of food gels within the mouth during mastication and in the stomach and small intestine when they breakdown through mechanical, chemical, or enzymatic mechanisms. Instead, it is typically more important to empirically establish the influence of GIT factors such as pH, ionic strength, bile salt concentration, and enzyme activity on the properties of a hydrocolloid gel, *e.g.,* swelling, shrinking, fragmentation, disassembly, or erosion (**Figure 4**). These processes can be controlled to design colloidal delivery systems that can trigger or control the release rate of bioactive agents in different regions of the GIT (Section 6). As an example, researchers have created "soft" and "hard" whey protein gels by varying the nature of the gelation mechanism used to produce them (Guo, et al., 2015). The authors found that under simulated gastric conditions (with pepsin) the soft gels disintegrated more rapidly, and led to faster gastric emptying, which could have important nutritional consequences. In other studies, it has been shown that the size of the pores in food gels impacts the rate of digestion of encapsulated macronutrients. For instance, it has been shown that the rate of lipid digestion is reduced when lipid droplets are encapsulated within hydrogel matrices, either made from proteins or polysaccharides, because the lipase has to penetrate through the gel network before accessing the lipid surfaces (Li, Hu, Du, Xiao, & McClements, 2011a; Sarkar, et al., 2015). In these examples, the rate of lipid digestion decreases as the mesh size of the polymer network decreases because it is more difficult for the digestive enzymes to penetrate.

3.6. Alteration of Mass Transport

It is often assumed that hydrocolloids that thicken or gel aqueous solutions will greatly slow down mass transport processes, but this depends on the nature of the molecules involved. It is important to distinguish between the *macro*-viscosity and the *micro*-viscosity of a hydrocolloid solution (Desmidt & Crommelin, 1991; Gulnov, Nemtseva, & Kratasyuk, 2016). The macro-viscosity is usually measured on bulk samples using conventional rheological instruments, such as shear viscometers or

dynamic shear rheometers. It depends on the resistance to flow of a material when a macroscopic force is applied. Conversely, the micro-viscosity is related to the resistance to movement that small molecules or small particles experience on a nano- or micro-scale, which is usually reflected by measuring their diffusion coefficient. The micro-viscosity can be measured using various methods, including particle tracking, dynamic light scattering, and fluorescence spectroscopy (Furst, Squires, Furst, & Squires, 2017; Vysniauskas & Kuimova, 2018). The micro- and macro-viscosity are fairly similar for simple solutions containing small molecules, such as water or a sugar solution. However, they can be orders of magnitude different for more complex solutions containing hydrocolloids, such as starch or gelatin (Gulnov, et al., 2016). A small molecule or particle may be able to travel unhindered through the spaces between a large hydrocolloid molecule and so experiences a local viscosity close to that of the pure solvent (usually water), even though the macro-viscosity can be very high (Basaran, Coupland, & McClements, 1999). On the other hand, the movement of large molecules or particles may be hindered when their dimensions are similar to or larger than the pore size in the hydrocolloid network (Burla, Sentjabrskaja, Pletikapic, van Beugen, & Koenderink, 2020). This phenomenon is important when considering the diffusion of bile salts or enzymes through gastrointestinal fluids that may contain hydrocolloids that thicken or gel them, or when considering the release of nutrients from gelled phases or microgels (McClements, 2017).

To a first approximation, the movement of non-interacting small particles (molecules, ions, or nanoparticles) through the pores in a spherical microgel can be described using the expression below (Crank, 1975; McClements, 2017):

$$\Phi = \frac{M(t)}{M(\infty)} = 1 - exp\left[-\frac{1.2D\pi^2}{Kr^2}t\right] \quad (9)$$

Here, Φ is the fraction of the particles that have diffused into or out of the microgels in time t, $M(t)$ and $M(\infty)$ are the particle concentrations in the microgels at time t and at equilibrium (infinite time), r is the radius of the microgels, D is the diffusion coefficient of the particles through the polymer network inside the microgels, and K is the equilibrium partition coefficient of the particles between the microgels and surrounding

fluid. The following expression has been derived to predict the hindered diffusion of particles through polymer networks (Chan & Neufeld, 2009; Zhang & Amsden, 2006):

$$D_{gel} = D_w \exp\left(-\pi\left(\frac{r_H + r_f}{\xi + 2r_f}\right)\right) \quad (10)$$

Here, D_{gel} and D_w are the diffusion coefficients of the particles through the polymer network and through pure water, respectively, r_H is the hydrodynamic radius of the particles, r_f is the cross-sectional radius of the polymer chains in the polymer network, and ζ is the diameter of the pores in the polymer network. The diffusion coefficient of the particles through the water can be related to their dimensions using the following expression (assuming they are roughly spherical):

$$D_w = k_B T / 6\pi\eta r_H \quad (11)$$

Here, k_B is Boltzmann's constant, T is absolute temperature, and η is the viscosity of the surrounding liquid (usually water). These equations can be used to better understand the factors that impact the release of components from hydrocolloid-based viscous solutions or gels present in the gastrointestinal tract through diffusion, such as the release of flavors in the mouth, the penetration of enzymes into food matrices in the stomach, or the release of bioactive agents from microgels in the small intestine. These equations predict that the mass transport rate of a flavor, enzyme, or bioactive agent should increase as the pore size in the polymer network increases. This knowledge can then be used to design hydrogel-based foods that slow down the digestion of macronutrients or that control the release of flavors or nutrients in the body.

Finally, it should be noted that the macro-viscosity may also impact the mass transport of foods and gastrointestinal components by altering mixing processes, which could alter nutrient digestion (Farres, Moakes, & Norton, 2014). For instance, if there are large clumps of gelled material in the GIT that contain macronutrients, the digestive enzymes may have to diffuse through these clumps to get to the lipids, proteins, or starches inside, thereby retarding their hydrolysis.

3.7. Water-holding Capacity and Gastrointestinal Transport

Many food hydrocolloids have good water-holding capacity (WHC) due to their ability to hold water through a capillary mechanism (Blackwood, et al., 2000; Stevenson, Dykstra, & Lanier, 2013). As a result, they can alter the rheology of the partially digested foods passing through the GIT. In particular, the presence of dietary fibers can increase the amount of water trapped in the stool as it passes along the colon, thereby making it softer and easier to move, which helps to prevent constipation and improve gut health.

To a first approximation, the Laplace pressure of a porous material is given by the following equation (Stevenson, et al., 2013):

$$\Delta P = 2\gamma \cos\theta / r \tag{12}$$

Here, ΔP is the capillary pressure, γ is the water–air surface tension, θ is the contact angle at the water-polymer interface, and r is the radius of the pores. The water holding capacity (WHC) of a porous food material is related to its ability to hold water against some external force, such as gravity or applied pressure. The WHC typically increases as the number of pores increases and the size of the pores decreases.

Thermodynamic models have been developed to relate the water holding capacity of polymer-based foods (such as meats or vegetables) to their chemical and structural properties (van der Sman, 2013; van der Sman, Paudel, Voda, & Khalloufi, 2013). These models relate the WHC of polymeric food materials to three main factors: (i) polymer-water mixing; (ii) impact of ion – polymer interactions; and (iii) elastic contributions due to deformation of the gel matrix. The theory is developed in terms of the swelling pressure:

$$\Pi_S = \Pi_M + \Pi_I + \Pi_E \tag{13}$$

$$\Pi_M = +\frac{RT}{v_W}[\ln(1-\phi) + \phi + \chi\phi^2] \tag{14}$$

$$\Pi_I = +\frac{RT}{v_W}\left[a_{w,I}\right] \tag{15}$$

$$\Pi_E = -\frac{RT}{v_W} N_C \phi_0 \left[\frac{1}{2}\left(\frac{\phi}{\phi_0}\right) - \left(\frac{\phi}{\phi_0}\right)^{1/3}\right] \quad (16)$$

Here, R is the gas constant, T is the absolute temperature, v_W is the molar volume of the water, ϕ is the volume fraction of the polymer molecules, χ is the Flory–Huggins interaction parameter, $a_{w,I}$ is the water activity of the added ions, N_C depends on the number density of polymer crosslinks, and φ_0 is the volume fraction of polymer at crosslinking (van der Sman, et al., 2013).

Mathematical models have also been developed to relate the microstructure and surface properties of colloidal gels to their water holding characteristics (Chang & Cheng, 2018; Smagin, 2018; Smagin, et al., 2019). These models were originally developed to predict the retention of water by colloidal soils but should also be suitable for application to colloidal foods. As expected, they predict that the water holding capacity of a material increases as the pore size decreases and the surface area increases. This relationship between capillary forces and WHC has been demonstrated empirically for gels made from non-food and food polymers: water increases as pore size decreases (Stevenson, et al., 2013). A better understanding of the physicochemical basis for the WHC of the gastrointestinal contents may lead to the design of functional foods that can prevent constipation and improve gut function.

3.8. Digestibility and Fermentability

Differences in hydrocolloid digestibility in different regions of the gastrointestinal tract can be employed to create smart colloidal delivery systems capable of releasing nutrients to targeted regions within the human gut (**Figure 5**). Some food hydrocolloids are digestible within the upper gastrointestinal tract, such as many proteins and starches (McClements, 2017). For instance, starch-based particles can be digested within the mouth by amylase and release their payload there. Conversely, protein- or lipid-based ones are digested in the stomach and small intestine and are therefore more suitable for delivery of payloads to these regions. Other food hydrocolloids (dietary fibers) are indigestible in the mouth, stomach, and small intestine, but are fermented by gut bacteria once they reach the colon. These fermentable hydrocolloids can be used to assemble dietary fiber-based particles that can deliver nutrients to the colon (McClements, 2017),

or they can serve as prebiotics to promote the growth of beneficial bacteria in the gut (Roberfroid, et al., 2010; Wang, 2009).

The digestibility and fermentability of food hydrocolloids are therefore important characteristics that can be used to control the gastrointestinal fate of nutrients, thereby improving human health and wellbeing. Potential applications of hydrocolloids for this purpose are discussed later.

4. The physiology and physiochemistry of the human gut

Before examining the impact of food hydrocolloids on the behavior of foods within the gastrointestinal tract it is useful to briefly discuss the digestion and absorption of nutrients and the importance of controlling these processes. Traditionally, food scientists have been primarily concerned with creating shelf-stable foods with desirable physicochemical and sensory properties. More recently, there has been interest in also designing foods so as to control their behavior within the human gut, so as to produce desirable nutritional or physiological effects, such as increased satiety, enhanced bioavailability, modulated pharmacokinetics, or targeted release (Chung, Smith, Degner, & McClements, 2016; Krop, et al., 2018; Sarkar, Ye, & Singh, 2017a). The design of these kinds of functional foods requires knowledge of the different regions of the gastrointestinal tract, the multiscale dynamic processes occurring there, and how they alter food properties (Bornhorst, Gouseti, Wickham, & Bakalis, 2016). Moreover, food and nutrition researchers are utilizing concepts and techniques developed in the pharmaceutical industry for drug delivery to better understand and control the gastrointestinal fate of foods (Gleeson, Ryan, & Brayden, 2016; Nowak, Livney, Niu, & Singh, 2019; Sarkar & Mackie, 2020). In particular, standardized *in vitro* and *in vivo* gastrointestinal and pharmacokinetic models are being increasingly adopted by food researchers. In this section, a brief overview of the journey of foods through the human gut is therefore given.

4.1. Mouth

Foods enter the human body through the mouth, whose initial purpose is to sample foods to determine whether they should be further processed or spat out. If the food is deemed acceptable, then the mouth converts it into a form that is suitable for swallowing

(Singh, Ye, & Horne, 2009). For fluid foods, this simply involves holding the food within the mouth before swallowing but for solid foods this may also involve a considerable amount of chewing to breakdown the structure and mix the food with the saliva. Saliva is a complex biological fluid with a pH around neutral that contains minerals, enzymes (amylase), antimicrobials, and mucin, which is a natural hydrocolloid that lubricates the oral surfaces and helps foods slip down the esophagus in the form of a bolus (Dawes, et al., 2015; Sarkar, Xu, & Lee, 2019). The time foods spend in the mouth varies from a few seconds to a few minutes depending on their textural characteristics, *e.g.,* low viscosity fluids *versus* hard chewy solids. It should be noted that hydrocolloids may make foods feel creamy, watery, slimy, or gritty within the mouth depending on their molecular and physicochemical characteristics. Consequently, the impact of hydrocolloids on mouthfeel is an important consideration when developing functional foods (Shewan, Pradal, & Stokes, 2020; Upadhyay, Aktar, & Chen, 2020).

4.2. Stomach

The stomach is a muscular cavity that contains highly acidic (pH 1-3) and enzymatically-active gastric fluids (Guo, Ye, Singh, & Rousseau, 2020; Singh, et al., 2009). The low pH of the stomach helps protect the body from harmful microbes that might be present in the ingested food. In addition, the stomach is designed to breakdown any remaining food structures through a combination of mechanical (churning), chemical (hydrochloric acid), and enzymatic (gastric lipase and pepsin) processes. On average, solid foods remain in the stomach for about 2 hours, but there is a broad range of residence times in practice. Before foods can enter the small intestine, they must pass through the pylorus sphincter, which is about 2 mm in diameter.

4.3. Small intestine

After passing through the pylorus sphincter, the partially digested food from the stomach ("chyme") enters the initial stages of the small intestine (duodenum). Alkaline pancreatic juices containing bile salts and digestive enzymes are squirted into the chyme causing its pH to become closer to neutral and initiating further hydrolysis of the macronutrients (Bohn, et al., 2018; Norton, Espinosa, Watson, Spyropoulos, & Norton, 2015; Singh, et al., 2009). Here, starches are broken down to glucose by amylases,

proteins are broken down to peptides and amino acids by proteases, and lipids are broken down to monoglycerides and free fatty acids by lipases (Boland, Golding, & Singh, 2014). The water-soluble digestion products diffuse through the intestinal fluids to the surfaces of the epithelium cells where they can be absorbed by active transporters in the cell membranes or by passive diffusion through the T-junctions that hold neighboring cells together. Small water-insoluble digestion products, such as fatty acids and monoglycerides, may be incorporated into mixed micelles that then carry them to the epithelium cells for absorption, where they are then re-assembled and packaged into lipoproteins that carry them through the bloodstream to other tissues (Ko, Qu, Black, & Tso, 2020). Large insoluble matter, such as dietary fibers, calcium soaps, and non-digestible lipids may not be absorbed within the small intestine, and so they move further down the GIT to the colon. The rate and degree of macronutrient digestion determines the pharmacokinetic (PK) profile of the nutrient metabolites in the bloodstream, such as glucose, lipoproteins, and peptides (**Figure 7**). The PK profile influences the total number of calories obtained from a food, as well as hormonal and metabolic responses that affect satiety, appetite, and insulin sensitivity.

4.4. Colon

Some food hydrocolloids are not digested or only partially digested within the upper gastrointestinal tract because they are resistant to hydrolysis by the enzymes secreted there (Grabitske & Slavin, 2009; Kumar, Sinha, Makkar, de Boeck, & Becker, 2012; Lattimer & Haub, 2010). This might occur because they contain covalent linkages (such as certain types of glycosidic bonds) that cannot be hydrolyzed by the digestive enzymes or because they are physically protected from digestion (*e.g.,* because they are trapped inside indigestible matrices or surrounded by indigestible coatings). Hydrocolloids that are not digested in the upper GIT may be hydrolyzed by enzymes secreted by the microbes residing in the colon. One of the main fermentation products arising from the digestion of dietary fibers are short chain fatty acids (SCFAs), such as acetate, propionate and butyrate, which act as a fuel source for the colonic enterocytes, as well as signaling molecules with the host. As a result, they play an important role in maintaining gut health. The type and amount of SCFAs and other metabolites produced in the colon impacts the nature and diversity of the gut bacteria, which plays a major role in human

health and wellbeing (Carlson & Slavin, 2016; Tabernero & de Cedron, 2017). Undigested proteins reaching the colon may also serve as a source of nutrients for the bacteria living in the colon. Controlling the types of hydrocolloids reaching the colon through food design approaches may therefore be important for controlling human health by modulating the gut microbiome.

5. Impact of Hydrocolloids on Nutrient Gastrointestinal Fate

5.1. Modulation of Mouthfeel and Flavor

Many hydrocolloids play an important role in the mouthfeel of both natural and processed foods, which is mainly due to their ability to alter the rheological properties of the food and saliva (Mosca & Chen, 2017; Wang & Chen, 2017), as well as coating and lubricating the surfaces of the mouth (Sarkar, Andablo-Reyes, Bryant, Dowson, & Neville, 2019; Sarkar, et al., 2017a). The nature of these effects depends on the molecular characteristics of the hydrocolloids, such as their molecular weight, conformation, polarity, and charge, because this impacts their ability to alter the fluid flow and to interact with saliva components and oral surfaces (Stokes, Boehm, & Baier, 2013). Many hydrocolloids greatly increase the viscosity of the bolus, which can either lead to an unpleasant gumminess/slipperiness or a desirable thickness/creaminess, depending on the nature of the effect (Upadhyay, et al., 2020; van Vliet, van Aken, de Jongh, & Hamer, 2009). Some proteins have been reported to have an astringent mouthfeel, which can be attributed to their tendency to bind to mucin and form insoluble complexes (Celebioglu, Lee, & Chronakis, 2020). As a result, the mucin is no longer able to lubricate the oral surfaces effectively (Fabian, Beck, Fejerdy, Hermann, & Fabian, 2015). Some peptides, formed by hydrolyzing proteins, have a bitter taste, which can reduce the desirable flavor profile of foods (Fu, Chen, Bak, & Lametsch, 2019). Consequently, it is important to prevent these peptides from being present in the mouth or to design food matrices that mask their bitterness.

The presence of hydrocolloids within the mouth may also alter the flavor profile of foods (Hollowood, Linforth, & Taylor, 2002; Taylor, 1996; Taylor & Linforth, 1996). Hydrocolloids alter the mixing of foods with saliva, as well as the movement of taste and aroma molecules from the food to flavor receptors in the mouth and nose. The ability of

hydrocolloids to modulate flavor release depends on numerous factors, with the most important being their ability to bind certain kinds of flavor molecules and to increase the viscosity of the oral contents. Many proteins and starches have accessible non-polar domains on their surfaces that can bind non-polar aroma molecules, which decreases the amount reaching the nasal cavity, thereby reducing flavor intensity (Kuhn, Considine, & Singh, 2006; Viry, Boom, Avison, Pascu, & Bodnar, 2018). Hydrocolloids may also delay the release of both taste and aroma molecules due to their ability to hinder their movement from the ingested food to the saliva and into the gas phase above the food (Hollowood, et al., 2002). Consequently, the type, concentration, and interactions of hydrocolloids in foods impacts flavor perception, which can be utilized to create foods with desirable mouthfeel and flavor release profiles.

5.2. Modulation of Gastrointestinal Transit

5.2.1. Gastric motility and emptying

The length of time a food remains in the stomach and the speed at which it is broken down due to mechanical, enzymatic, and chemical processes affects the rate of nutrient release and absorption (Ratanpaul, Williams, Black, & Gidley, 2019). In turn, this influences the timing of hormone release in response to food ingestion, which impacts hunger, satiety, and satiation, and therefore the frequency and quantity of food consumed (Bruen, O'Halloran, Cashman, & Giblin, 2012; Halford & Harrold, 2012). Some hydrocolloids are able to increase the viscosity of the gastric fluids, which slows gastric emptying and macronutrient digestion (Guo, et al., 2020; Qi, Al-Ghazzewi, & Tester, 2018). This delay in gastric emptying may increase the feelings of satiety and satiation, thereby reducing the total amount of calories consumed, leading to health benefits by reducing body weight. Moreover, they may be able to control hormone levels thereby improving metabolic health. The impact of food hydrocolloids on gastric motility and emptying may therefore influence chronic diseases related to overeating, such as obesity, diabetes, and heart disease. Slower gastric emptying may also help to prevent spikes in the concentration of sugars or lipids in the bloodstream, which can enhance metabolic health.

627 *5.2.2. Colonic flow*

628 The speed that non-adsorbed foods move through the colon may also have important
629 health effects. As mentioned earlier, the main factor impacting the rheology of the
630 gastrointestinal contents in the colon is the absorption of water, which depends on
631 capillary forces generated by the hydrocolloid network inside (Stevenson, et al., 2013).
632 Dietary fibers form a 3D-network within the gastrointestinal contents in the colon, which
633 can entrain large quantities of water through capillary forces. As a result, the rheological
634 properties of the gastrointestinal contents in the colon are highly dependent on the type
635 and amount of dietary fiber present, which influences the speed and ease at which they
636 can pass through the lower GIT (Blackwood, et al., 2000). In principle, a diet low in
637 fiber leads to a more rigid solid-like mass that moves slowly, whereas a diet high in fiber
638 leads to a more fluid-like mass that passes through more rapidly, thereby reducing
639 constipation. Nevertheless, not all dietary fibers are effective at reducing constipation,
640 with many fibers having little or no effect (Gelinas, 2013). Indeed, in a recent review it
641 was stated that "to exert a laxative effect, fiber must: (1) resist fermentation to remain
642 intact throughout the large bowel and present in stool, and (2) significantly increase stool
643 water content and stool output, resulting in soft/bulky/easy-to-pass stools." (McRorie &
644 Chey, 2016). As a specific example, a study with preterm infants showed that
645 supplementation of their meals with prebiotic oligosaccharides reduced stool viscosity
646 and reduced transit times (Mihatsch, Hoegel, & Pohlandt, 2006). In future, more research
647 is required to identify those hydrocolloids that are most effective at increasing the rate of
648 transit of foods through the colon.
649

650 **5.3. Modulation of Macronutrient Digestion and Absorption**

651 The presence of hydrocolloids in foods can modulate the digestion and/or absorption
652 of macronutrients, such as fats, starches, and proteins. In some cases, they decrease the
653 rate and extent of these processes, whereas in other cases they may have little effect, or
654 even the opposite effect, depending on their nature and concentration. In this section,
655 some of the major mechanisms that hydrocolloids can modulate nutrient digestion and
656 absorption are highlighted.

5.3.1. Rheological modification of gastrointestinal fluids

The presence of hydrocolloids within a food may alter the rheological properties of the gastrointestinal fluids, which then impacts the digestion and absorption of macronutrients. For instance, some hydrogels can form highly viscous solutions or gels within the gastrointestinal tract (Farres, et al., 2014). A study with an *in vitro* GIT model, which included segmentation forces in the small intestine, showed that adding a thickening agent (guar gum) to the simulated intestinal fluids reduced the rate of glucose release after starch hydrolysis (Tharakan, et al., 2010). Adding this kind of hydrocolloid may therefore be useful for designing foods for diabetics, who would benefit from a low and sustained level of glucose within their bloodstream, rather than experiencing large spikes. Hydrocolloids may also thicken or gel the gastric fluids, which reduces the mixing of the different constituents within the stomach (Farres, et al., 2014). As a result, it is more difficult for the digestive enzymes to reach the macronutrients and hydrolyze them. For instance, fat droplets or starch granules may be trapped within highly viscous or gelled regions within the stomach that enzymes can only reach slowly by diffusing through the biopolymer network.

5.3.2. Binding interactions

As mentioned earlier, the binding of gastrointestinal constituents to ingested food hydrocolloids may alter the way foods behave inside the human gut. Understanding and controlling these interactions may therefore be used to improve human nutrition. In general, binding may occur due to a number of different kinds of molecular forces, depending on the nature of the molecules involved and the gastrointestinal environment (such as pH and ionic composition). For instance, binding may occur due to electrostatic, hydrophobic, hydrogen bonding, or van der Waals interactions, or some combination of these forces (Israelachvili, 2011). Consequently, it is important to elucidate the primary types of molecular interactions that each kind of hydrocolloid can participate in, and to identify the key molecular features that lead to these interactions, such as the number and location of charged, polar, or non-polar groups.

In vitro studies have shown that nanocrystalline cellulose (NCC) can inhibit the activity of α-amylase and α-glucosidase in model foods containing cooked potato starch

687 and protein (Nsor-atindana, Yu, Goff, Chen, & Zhong, 2020). The degree of inhibition
688 was reported to increase as the dimensions of the NCC decreased, which was probably
689 due to the increase in surface area. The authors postulated that the enzymes bound non-
690 specifically to the NCC, which reduced its activity against the starch. Other *in vitro*
691 studies have shown that α-amylase activity is inhibited in the presence of cellulose,
692 which was attributed to the binding of the enzyme to this dietary fiber (Dhital, Gidley, &
693 Warren, 2015). This type of hydrocolloid may therefore be useful for slowing down the
694 digestion of starches in the human GIT, thereby reducing glucose spikes, which may
695 again be useful for designing foods for diabetics.
696 Cationic chitosan can bind to anionic fatty acids or bile acids in the small intestine
697 through electrostatic interactions, which causes them to precipitate, thereby reducing the
698 bioaccessibility of oil-soluble vitamins, like vitamin D (Tan, et al., 2020). Similarly,
699 anionic alginate molecules can bind to cationic calcium anions in the stomach or small
700 intestine, which can alter the gastrointestinal fate of nutrients. For example, *in vitro*
701 experiments have shown that alginate can retard lipid digestion by binding to calcium
702 ions in the simulated small intestine (Hu, et al., 2010; Qin, Yang, Gao, Yao, &
703 McClements, 2016). The origin of this effect is that free calcium ions are normally
704 needed to precipitate long-chain fatty acids that accumulate at the lipid droplet surfaces
705 during digestion. If there are no free calcium ions available to remove these fatty acids,
706 then lipase may not be able to reach the underlying triglycerides. Human studies have
707 shown that ingestion of high alginate levels can increase the fraction of free fatty acids
708 excreted in the stool, which was attributed to the formation of alginate gels that trapped
709 them (Sandberg, et al., 1994). The binding of bile salts to dietary fibers in the small
710 intestine can reduce blood cholesterol levels, since they are excreted in the feces, so the
711 body has to utilize endogenous cholesterol to synthesize more bile salts (Singh, Metrani,
712 Shivanagoudra, Jayaprakasha, & Patil, 2019). *In vitro* isothermal titration calorimetry
713 (ITC) measurements have confirmed that bile salts can bind to chitosan mainly through
714 electrostatic interactions (Thongngam, et al., 2005). Hydrocolloids that can strongly bind
715 bile salts may therefore be useful for reducing the cholesterol levels in individuals who
716 are prone to heart disease.

5.3.3. Aggregation state

The presence of hydrocolloids may alter the aggregation state of macronutrient particles (such as fat droplets, starch granules, or protein particles) within the stomach or small intestine, thereby altering the surface area that is exposed to digestive enzymes in the gastrointestinal fluids (McClements, Decker, Park, & Weiss, 2009; Zhang, Zhang, Zhang, Decker, & McClements, 2015). Experiments have shown that the rate of macronutrient digestion increases as their surface area increases (particle size decreases). For instance, the rate of lipid digestion in emulsions has been reported to increase as the surface area of lipids exposed to lipases increases in simulated gastrointestinal studies (Li & McClements, 2010b; Salvia-Trujillo, Qian, Martin-Belloso, & McClements, 2013). Similarly, the digestion rate of starch granules and protein particles by amylases or proteases has been reported to increase as their surface area increases (Tamura, Okazaki, Kumagai, & Ogawa, 2017; Xing, et al., 2016).

If macronutrient particles form tightly packed clusters, then it is more difficult for the enzymes to access the surfaces of the particles in the interior of the clusters (**Figure 6**), which slows down digestion. Hydrocolloids can either promote or inhibit macronutrient digestion by inhibiting or promoting particle aggregation within the GIT. For instance, pectin has been shown to inhibit the flocculation of gelatin-coated oil droplets in the stomach, which increased the subsequent rate of lipid digestion in the small intestine by increasing the surface area of lipid droplets exposed to the lipase (Zeeb, Weiss, & McClements, 2015). Similarly, the presence of xanthan gum or pectin (two anionic polysaccharides) was shown to increase the digestibility of hydrolyzed rice glutelin-stabilized fish oil-in-water emulsions, which was attributed to their ability to reduce droplet aggregation in a simulated GIT (Xu, Sun, & McClements, 2020). Conversely, the presence of chitosan was shown to promote the flocculation of lipid droplets in the stomach and small intestine, which decreased the rate of lipid hydrolysis (Qin, et al., 2016). Consequently, it may be possible to modulate the digestibility of macronutrients within the human gut by adding hydrocolloids that either promote or inhibit their aggregation. Hydrocolloids that inhibit macronutrient digestion through this mechanism may be useful for creating functional foods that suppress sugar or lipid spikes in the blood. Conversely, hydrocolloids that promote digestion may be used to increase the

748 bioavailability of beneficial macronutrients, such as proteins.

749 *5.3.4. Interfacial modification and embedding*

750 Macronutrient digestion may also be modulated by the properties of any coatings
751 surrounding the fat, starch, or protein particles within a food (**Figure 6**). These thin
752 coatings can inhibit the ability of digestive enzymes to access the surfaces of the
753 macronutrients, thereby delaying their digestion (McClements, et al., 2010). For
754 instance, anionic polysaccharides may form coatings around cationic lipid droplets in the
755 stomach, which reduces the ability of lipases to access the emulsified lipids in the small
756 intestine (Araiza-Calahorra & Sarkar, 2019; Qin, et al., 2016). A recent study showed
757 that lipid droplets coated by a 3-layer coating (lactoferrin, alginate and polylysine) had a
758 higher digestibility and carotenoid bioaccessibility than those coated by 1- or 2-layers,
759 which was attributed to the ability of the 3-layer coatings to protect the droplets from
760 aggregation in the simulated GIT (Gasa-Falcon, Acevedo-Fani, Oms-Oliu, Odriozola-
761 Serrano, & Martin-Belloso, 2020). Another recent study showed that coating whey
762 protein-coated oil droplets with chitosan increased the bioaccessibility of curcumin in a
763 simulated GIT model, as well as the uptake of curcumin by a cell culture model (Gasa-
764 Falcon, et al., 2020). Adsorbing carboxymethyl cellulose (CMC) to the surfaces of whey
765 protein-coated rapeseed oil droplets was shown to reduce the rate and extent of lipid
766 digestion within *in vitro* and *in vivo* (rat feeding) studies (Malinauskyte, et al., 2018).
767 Studies have shown that coating fat droplets with particle-based emulsifiers (zein-PGA
768 nanoparticles) rather than conventional molecular-based emulsifiers (lactoferrin or
769 rhamnolipid) reduced lipid digestion and carotenoid bioaccessibility, which was
770 attributed to their ability to inhibit lipase accessing the emulsified lipid phase (Wei, et al.,
771 2020). Similarly, other types of particle-based emulsifier have been shown to be effective
772 at inhibiting lipid or protein digestion in emulsions, including whey protein microgels
773 (Araiza-Calahorra, Wang, Boesch, Zhao, & Sarkar, 2020b; Sarkar, et al., 2016), whey
774 protein-dextran conjugate microgels (Araiza-Calahorra, Glover, Akhtar, & Sarkar, 2020a;
775 Araiza-Calahorra, et al., 2020b), cellulose nanofibers (Winuprasith, et al., 2018), and
776 cellulose nanocrystals (Sarkar, Zhang, Murray, Russell, & Boxal, 2017b). Numerous
777 other studies have shown that modulating the interfacial layers of fat droplets can alter
778 lipid bioaccessibility and/or nutraceutical bioaccessibility (Hu, Li, Decker, Xiao, &

779 McClements, 2011; Li, et al., 2010a; McClements, et al., 2010; Pinheiro, Coimbra, &
780 Vicente, 2016; Sarkar, Li, Cray, & Boxall, 2018). In particular, the importance of
781 molecular *versus* particulate and digestible *versus* indigestible interfacial coatings has
782 been stressed (Sarkar, Zhang, Holmes, & Ettelaie, 2019). Typically, indigestible
783 particulate coatings are more effective at inhibiting macronutrient digestion, provided
784 they remain attached to the macronutrient surfaces.
785 The digestion of macronutrients may also be inhibited when they are embedded
786 within hydrogel particles (**Figure 6**). For instance, the rate and extent of lipid digestion
787 has been shown to decrease when fat droplets are embedded within calcium alginate
788 microgels (Li, et al., 2011a). The degree of inhibition in lipid digestion increased as the
789 microgel dimensions increased, as well as when the pore size in the biopolymer network
790 decreased, which can be attributed to the longer distance the lipase molecules have to
791 travel to reach the entrapped fat droplets and the greater hindered diffusion, respectively.
792 Encapsulation of lipid droplets in other kinds of hydrogel-based microgels has also been
793 shown to inhibit their digestion, including those fabricated from carrageenan (Zhang, et
794 al., 2016), alginate-chitosan (Li & McClements, 2011b), gellan gum (Vilela, Perrechil,
795 Picone, Sato, & da Cunha, 2015) and egg white proteins (Gu, et al., 2017). Thus, the
796 lipid digestion profile can be modulated by controlling the type of hydrocolloids used to
797 create microgels, as well as the fabrication conditions, as this will affect how the
798 microgels response in different regions of the GIT (Figure 5) (McClements, 2017).
799 Encapsulation within microgels has also been utilized to reduce the digestion of other
800 macronutrients, such as proteins (Zhang, Zhang, & McClements, 2017) and starches
801 (Rose, et al., 2009). This approach may therefore be suitable for creating a new
802 generation of functional foods that can modulate the rate of macronutrient digestion,
803 thereby controlling blood metabolite levels and hormonal responses after food ingestion.

804 *5.3.5. Gastrointestinal barrier properties*

805 Some hydrocolloids alter the absorption of bioactive substances by changing the
806 permeability of the mucus layer or epithelium cells. For instance, chitosan has been
807 reported to act as a permeation enhancer for certain kinds of bioactive agents (Canali,
808 Pedrotti, Balsinde, Ibarra, & Correa, 2012), which has at least partly been attributed to its
809 ability to bind to and increase the dimensions of the tight junctions between epithelium

cells (Schipper, et al., 1997; Thanou, Verhoef, & Junginger, 2001)

5.3.6. Alteration of chemical stability of nutrients

In addition to their normal hydrolysis by digestive enzymes in the GIT, some macronutrients may undergo other kinds of chemical changes in the gastrointestinal tract that can impact their health effects. In particular, polyunsaturated lipids are prone to oxidation under certain gastrointestinal conditions (Kerem, Chetrit, Shoseyov, & Regev-Shoshani, 2006; Larsson, Cavonius, Alminger, & Undeland, 2012; Nieva-Echevarria, Goicoechea, & Guillen, 2020). As a result, they may form toxic reaction products that can be absorbed by the human body and cause health problems (Goicoechea, Brandon, Blokland, & Guillen, 2011). Some hydrocolloids (or their digestion products) are known to have strong antioxidant properties (McClements & Decker, 2018; Sarmadi & Ismail, 2010; Teixeira, Pires, Nunes, & Batista, 2016), and so their presence within a food may be able to inhibit the chemical degradation of polyunsaturated lipids in the GIT. Various kinds of food proteins and polysaccharides have been shown to exhibit antioxidant effects through different physicochemical mechanisms, including chelation of transition metal ions and free radical scavenging effects (Laguerre, Lecomte, & Villeneuve, 2007; Nieva-Echevarria, et al., 2020).

5.4. Modulation of Nutrient Bioavailability

A widely explored application of hydrocolloids has been to alter the pharmacokinetics (PK) and bioavailability of nutrients, *i.e.,* macronutrients, micronutrients, and nutraceuticals. The PK profile of an ingested bioactive component describes the change in its concentration in a specific tissue, often the systemic circulation, over time (**Figure 7**). As discussed in Section 5.3, this information is important because it influences the bodies hormonal and metabolic responses to ingested macronutrients, which influences an individual's susceptibility to overeating, obesity, and diabetes. The PK profile is also important because it determines the bioavailability of nutrients. A number of key events contribute to the bioavailability of these bioactive substances, which can be summarized by the following expression (Yao, Xiao, & McClements, 2014):

$$BA = B^* \times A^* \times D^* \times M^* \times E^* \quad (17)$$

In this expression: B* represents *bioaccessibility* – the fraction of nutrient in the intestinal fluids in a form that can be absorbed; A* represents *absorption* – the fraction of the bioaccessible nutrients that are actually absorbed by the body; D* represents *distribution* – the fraction of the absorbed nutrients in the target tissues (often the bloodstream) after distribution around the body; M* is the *metabolism* – the fraction of nutrients in a bioactive form after any chemical or biochemical reactions inside the human body (before or after absorption); and, E* is the *excretion* – the fraction of the bioactive nutrient that has not been removed from the body, *e.g., via* the feces or urine. Typically, one or more of these phenomena may limit the overall bioavailability of a nutrient, depending on its molecular and physicochemical properties (McClements, Li, & Xiao, 2015). Each of these phenomena is time-dependent, which causes the nutrient levels in the bloodstream or other tissues to vary over time. For instance, the nutrient levels in the blood will typically increase sometime after ingestion of a food, reach a maximum level, and then decrease as they are distributed, metabolized and excreted (**Figure 7**).

Food hydrocolloids may alter the PK profile of nutrients in a number of ways (Boland, et al., 2014; McClements, et al., 2009), many of them discussed in detail in the previous section:

- Some hydrocolloids (particularly proteins) have strong buffering capacities and can therefore leader to a higher pH in the stomach after ingestion of a food, which can alter the aggregation state of macronutrients and the activity of digestive enzymes (such as gastric lipase and pepsin).
- Some hydrocolloids thicken or gel the gastrointestinal fluids, which can alter mixing and mass transport processes.
- Some hydrocolloids alter the aggregation state of macronutrients, which influences the surface area exposed to digestive enzymes. Hydrocolloids that promote aggregation, tend to inhibit digestion and reduce bioavailability, whereas those that prevent aggregation have the opposite effect.
- Some hydrocolloids form protective coatings around macronutrients, which inhibits the ability of digestive enzymes from reaching them, thereby slowing

digestion and reducing bioaccessibility.

- Some hydrocolloids bind gastrointestinal components (such as bile salts, calcium, or enzymes), which can either promote or inhibit digestion and bioaccessibility.
- Some hydrocolloids have antioxidant properties and can therefore reduce the chemical degradation of nutrients in the GIT.
- Some hydrocolloids increase the permeability of the intestinal membrane, thereby increasing absorption.

It is therefore possible to control the PK profiles of nutrients by controlling the type, concentration, and structural organization of hydrocolloids in foods, which may be useful for designing more effective functional foods to improve human health and wellbeing. In some cases, the presence of hydrocolloids in foods may have beneficial effects on nutrient absorption by increasing the bioavailability of oil-soluble vitamins or nutraceuticals. In other cases, they may have the opposite effect. For instance, the ability of chitosan to promote the precipitation of mixed micelles in the small intestine can reduce the bioaccessibility of oil-soluble vitamins, such as vitamin D (Tan, et al., 2020). In general, any dietary fiber that retards lipid digestion can also reduce the bioaccessibility of encapsulated bioactive substances by decreasing the fraction released from the oil droplets, as well as by reducing the amounts of mixed micelles formed to solubilize them (Winuprasith, et al., 2018; Zhou, et al., 2020). Consequently, it is important to carefully consider the overall impact of hydrocolloids on the gastrointestinal fate of foods and nutrient bioavailability.

5.5. Modulation of Gut microflora

The complex community of microorganisms residing in the human colon, collectively known as the gut microbiome, influences our susceptibility to chronic diseases such as obesity, inflammatory bowel diseases, autoimmune diseases, diabetes, atherosclerosis, and mental illnesses, and so plays a critical role in our health and wellbeing (Albenberg & Wu, 2014; Chassaing, Vijay-Kumar, & Gewirtz, 2017; Dinan & Cryan, 2017; Kataoka, 2016; Lloyd-Price, Abu-Ali, & Huttenhower, 2016; Tuddenham & Sears, 2015). Fostering a healthy ecosystem within the human gut is therefore believed to be critical for ensuring a healthy population. The bacteria living in the gut digest food

that is not digested and absorbed in the upper GIT, thereby extracting additional calories that can be utilized as energy. They transform some of these food remnants into new substances that may be advantageous to human health, such as vitamins, essential amino acids, and short chain fatty acids. They can detoxify harmful substances in our foods, such as the toxins found in some plant-based foods, by chemically transforming them. They may also generate signaling molecules (such as hormones) that communicate with the human body and regulate appetite, moods, and emotions. Finally, a healthy gut microbiome can help to train and strengthen the human immune system, thereby leading to improved overall health.

Hydrocolloids, such as polysaccharides and proteins, impact the type and number of microbes residing within the gut microbiome (Cockburn & Koropatkin, 2016; Porter & Martens, 2017; Yao, Muir, & Gibson, 2016). Consequently, there is considerable interest from food, nutrition, and clinical scientists in controlling the gut microbiome by supplementing the diet with beneficial hydrocolloids. Consuming high levels of digestible carbohydrates (rapidly digestible starches) has an adverse effect on the gut microbiome, whereas consuming high levels of non-digestible carbohydrates (dietary fibers) has beneficial effects. Nevertheless, the effects of specific dietary fibers depend on their precise molecular and physicochemical properties. One of the most important attributes of fermentable dietary fibers is their ability to generate short chain fatty acids (SCFAs) in the colon that act as an energy source, as well as produce regulatory molecules that send signals to our bodies that modulate our metabolisms, reduce inflammation, and communicate with our brains.

Dietary proteins may also have an impact on the human microbiome (Oliphant & Allen-Vercoe, 2019; Yao, et al., 2016). Indeed, diets high in proteins and low in carbohydrates were reported to have undesirable effects on the composition and function of the gut microbiome (Yao, et al., 2016). Meat proteins contain relatively high levels of L-carnitine, an amino acid that can be converted into trimethylamine N-oxide (TMAO) by the gut microbes in the colon, which is a substance linked to coronary heart disease (Zeisel & Warrier, 2017). On the other hand, plant proteins do not contain high levels of L-carnitine and may therefore be better for heart health.

6. Hydrocolloids in Foods

Hydrocolloids may be incorporated into the human diet in a variety of ways. They may simply be added as functional ingredients, such as thickening agents, gelling agents, or stabilizers. Alternatively, they may be used to create complex structures in foods that alter the way nutrients behave, such as colloidal delivery systems. Finally, they may be naturally present in whole foods, such as fruits, vegetables, cereals, nuts, or seeds, which may be eaten raw or cooked, thereby altering their properties and behavior within the human body. In this section, a brief overview of the impact of hydrocolloids in these different kinds of application on the gastrointestinal fate of foods is given.

6.1. Hydrocolloids as Functional Ingredients

Hydrocolloids are often added to foods as thickeners, gelling agents, stabilizers, or emulsifiers (Phillips, et al., 2009). In this case, they are usually being employed to obtain some desirable techno-functional attribute in a food such as appearance, texture, shelf-life, or mouthfeel. Until recently, the potential of using the same functional ingredients to modulate the behavior of foods inside the human body was not actively considered. Nevertheless, there is great potential for using hydrocolloids as multipurpose functional ingredients, to create desirable food and gastrointestinal effects. In this case, it is important to select ingredients that have the desired techno-functional properties (such as food texture and stability), as well as the desired nutritional properties (such as delayed macronutrient absorption or increased nutraceutical bioavailability). In many cases, this may require reformulation of existing products.

6.2. Hydrocolloid-based Delivery Systems

Hydrocolloids can be used to assemble complex colloidal structures in foods that can be used to encapsulate, protect, and deliver bioactive components (**Figure 8**). These kinds of delivery systems have been reviewed in detail elsewhere and so only a brief overview will be given here (McClements, 2017; Shewan, et al., 2013).

- *Emulsions*: Oil-in-water emulsions or nanoemulsions can be formulated using hydrocolloids as emulsifiers (McClements, et al., 2017). Hydrophobic nutrients can be located inside the oil droplets, amphiphilic nutrients at the oil-water interface, and hydrophilic nutrients in the water phase. Consequently, a

combination of different nutrients can be incorporated into a single delivery system.

- *Biopolymer nanoparticles:* Protein and/or polysaccharide nanoparticles that contain densely packed hydrocolloid molecules and little water can be formed using antisolvent precipitation methods (Joye & McClements, 2013). Nanoparticles assembled from hydrophobic proteins, such as zein or gliadin, are commonly used to encapsulate hydrophobic nutrients.
- *Microgels*: Microgels are small particles that consist of a network of protein and/or polysaccharide molecules and a relatively large amount of water (Zhang, et al., 2017). They can be fabricated using many different approaches using gelling hydrocolloids, including injection, templating, molding, and phase separation methods. Hydrophilic nutrients can be trapped inside them, provided they are sufficiently large and/or they stick to the molecules that make up the gel network. Hydrophobic nutrients can be encapsulated inside oil droplets first, which are then incorporated into the microgels. It is even possible to create microgel-in-microgel systems to achieve special effects, such as improved protection or sequential release of different components (Ma, Tu, Wang, Zhang, & McClements, 2018).

6.3. Hydrocolloids in whole foods

In many whole foods, the hydrocolloids are present in their natural environment, such as intracellular or intercellular regions. The cell walls of edible plants consist of complex hydrocolloid matrices comprised mainly of cellulose, hemicellulose, and pectin (Holland, Ryden, Edwards, & Grundy, 2020). The presence of these cell walls alters macronutrient digestion and phytochemical bioavailability by acting as steric barriers that inhibit the ability of digestive fluids from coming into contact with the proteins, starches, and lipids trapped inside the cells. When the cellular structures of plants are broken down, the macronutrients are released making them more readily digestible. Moreover, the phytochemicals may also be released from the cells making them more bioavailable in the GIT. The disruption of the cell walls through food processing may therefore have either detrimental or beneficial effects on animal and human nutrition depending on the system. More rapid digestion of starch or fats may lead to spikes in blood sugar or lipid

levels, which can cause dysregulation of the metabolism and endocrinal systems, leading to chronic diseases such as diabetes and obesity. Conversely, the enhanced release of proteins or phytochemicals (such as carotenoids) may have beneficial effects due to their health-promoting effects.

As an example, an *in vitro* study of the digestion of rice, showed that the uncooked rice was less hydrolyzed than cooked rice, but that partially cooked rice (10 min) was hydrolyzed the same as fully cooked rice (20 min) (Tamura, Singh, Kaur, & Ogawa, 2016). The authors suggested that the presence of the bran around the starch granules in the uncooked rice were able to prevent the amylase from digesting the starch molecules. Other studies have also shown that starch digestion is inhibited by the presence of intact plant cell walls, as well as the degree of starch crystallinity, which depends on the degree of thermal processing (Li, et al., 2020). This suggests, that the location of the indigestible fibers relative to the macronutrient is important. In future, more work is required to understand the structural organization of plant-based foods, how they breakdown inside the human body, and how this impacts their nutritional attributes.

7. Potential Health Benefits of Food Hydrocolloids

Certain kinds of food hydrocolloids, particularly dietary fibers, are claimed to exhibit specific health benefits when consumed regularly at sufficiently high quantities. Recently, a comprehensive review and meta-analysis of the potential health benefits of dietary fibers was carried out (Reynolds, et al., 2019). The authors included data that was equivalent to 135 million person-years taken from 185 prospective studies and 58 clinical trials on 4635 adults. It was reported that there was a 15–30% reduction in deaths or incidences of a range of chronic diseases, including all-cause mortality, cardiovascular disease, coronary heart disease, stroke, type 2 diabetes, and colorectal cancer in observational studies that compared people consuming the highest levels of dietary fiber to those consuming the lowest levels. Moreover, people consuming high dietary fiber levels were also shown to have lower bodyweights, blood pressures, and cholesterol levels in clinical trials. The researchers reported that the greatest reduction in risk from chronic disease could be achieved by consuming around 25 to 29 g of dietary fiber a day, which is much higher than the levels consumed by the majority of people, in both

developed and developing countries. Interestingly, the authors only found a weak link between overall disease risk and the glycemic index or glycemic load of a diet. Even so, there was some evidence that diets with a low glycemic index or glycemic load did reduce incidences of stroke and type 2 diabetes. Increased consumption of fiber-rich fruits and vegetables has also been linked to a reduced risk of cardiovascular disease, cancer and all-cause mortality in a systematic review and meta-analysis of the data (Aune, et al., 2017).

Overall, these studies suggest that it is important for consumers to eat more dietary fiber-rich foods to improve their health. Many of the health benefits reported for dietary fibers are related to the physicochemical and physiological processes that occur in the human gut after ingestion of food hydrocolloids discussed earlier, such as bile salt binding (cholesterol reduction), modulation of macronutrient digestion, fermentation in the colon, and alteration of stool rheology. The amount of dietary fibers in the diet can be increased by consuming more fruits, vegetables, grains, and nuts, however many people do not eat enough of these foods due to economic, social, or personal reasons. There are therefore opportunities to increase the level of dietary fibers in processed foods to enhance their healthiness, but there is some question about whether this approach will have the same health benefits. In other words, dietary fibers may have different effects inside the human gut when they are an integral part of natural foods (such as fruits, vegetables, or whole grains) than when they are isolated and added to processed foods as functional ingredients (Grundy, et al., 2016a; Grundy, Lapsley, & Ellis, 2016b; Guo, Ye, Bellissimo, Singh, & Rousseau, 2017b). This is an another important area for future research.

It should be noted that there may also be adverse effects associated with consuming large quantities of certain dietary fibers, including bloating, gastrointestinal discomfort, flatulence, and loose stools, especially in individuals with bowel disorders (Nyyssola, Ellila, Nordlund, & Poutanen, 2020). These effects depend on the type and amount of dietary fibers consumed, as well as the nature of the foods they are consumed with. Consequently, both the health benefits and potential risks of fortifying foods with high levels of dietary fibers should be carefully considered when formulating functional foods.

8. Conclusions

Hydrocolloids have been used as techno-functional ingredients in foods and beverages for decades, *e.g.,* as thickening, gelling, emulsifying, or stabilizing agents. More recently, there has been a focus on their ability to modulate the processes occurring within the human gastrointestinal tract after the ingestion of foods. Researchers are attempting to develop structure-functional relationships for different hydrocolloids that link their molecular characteristics (such as molar mass, conformation, branching, charge, and polarity) to their ability to modulate specific gastrointestinal processes (such as mass transport, binding, solubilization, and absorption). As our understanding of these complex relationships increases it should be possible to design functional foods with specific health benefits, *e.g.,* the ability to increase nutraceutical or vitamin bioavailability, reduce fat or starch digestion, increase the satiety response, reduce cholesterol levels, decrease susceptibility to colonic diseases, or foster a healthy gut microbiome.

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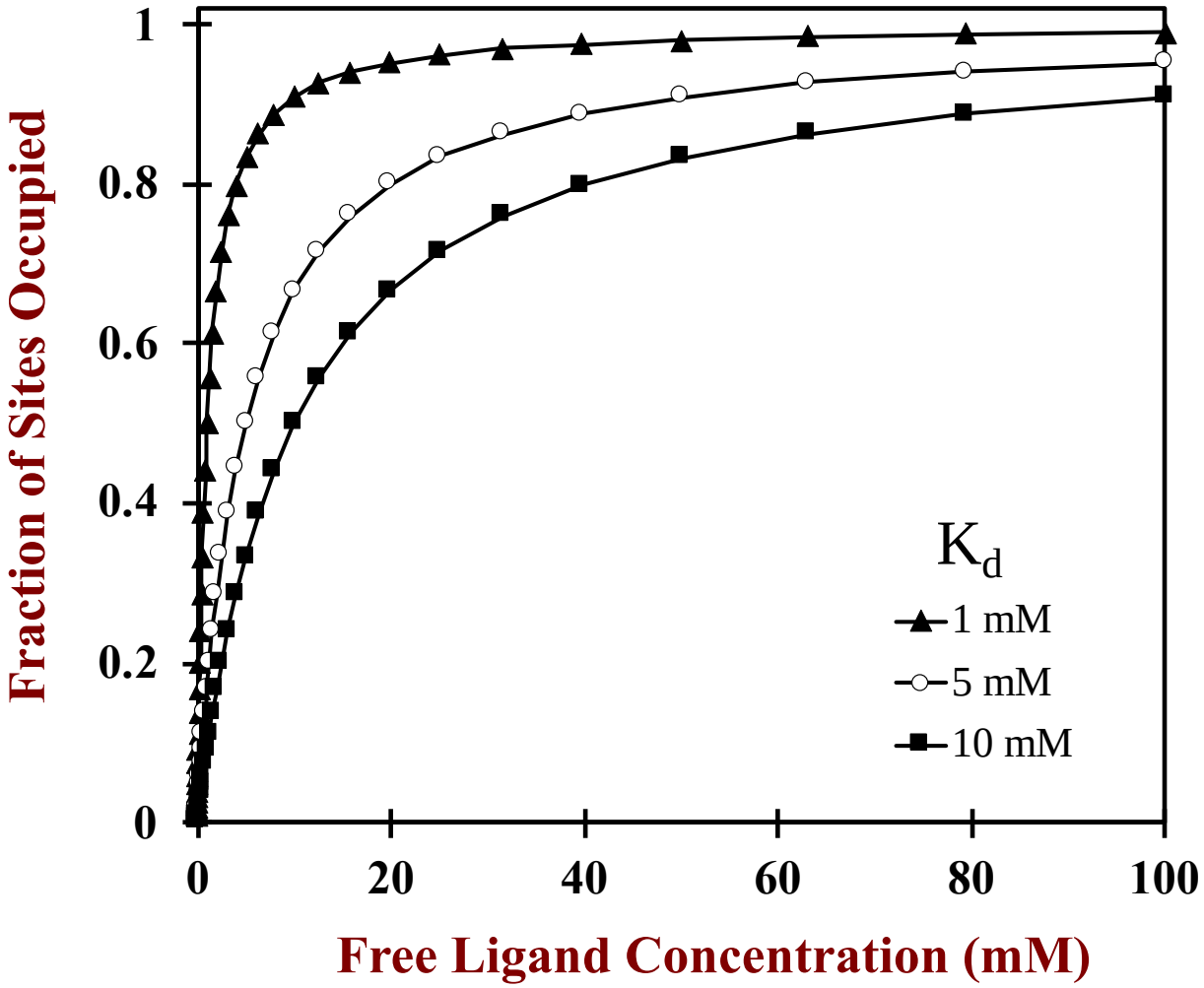


Figure 1. The fraction of sites occupied on a receptor molecule increases as the lignd concentration and binding affinity increase.

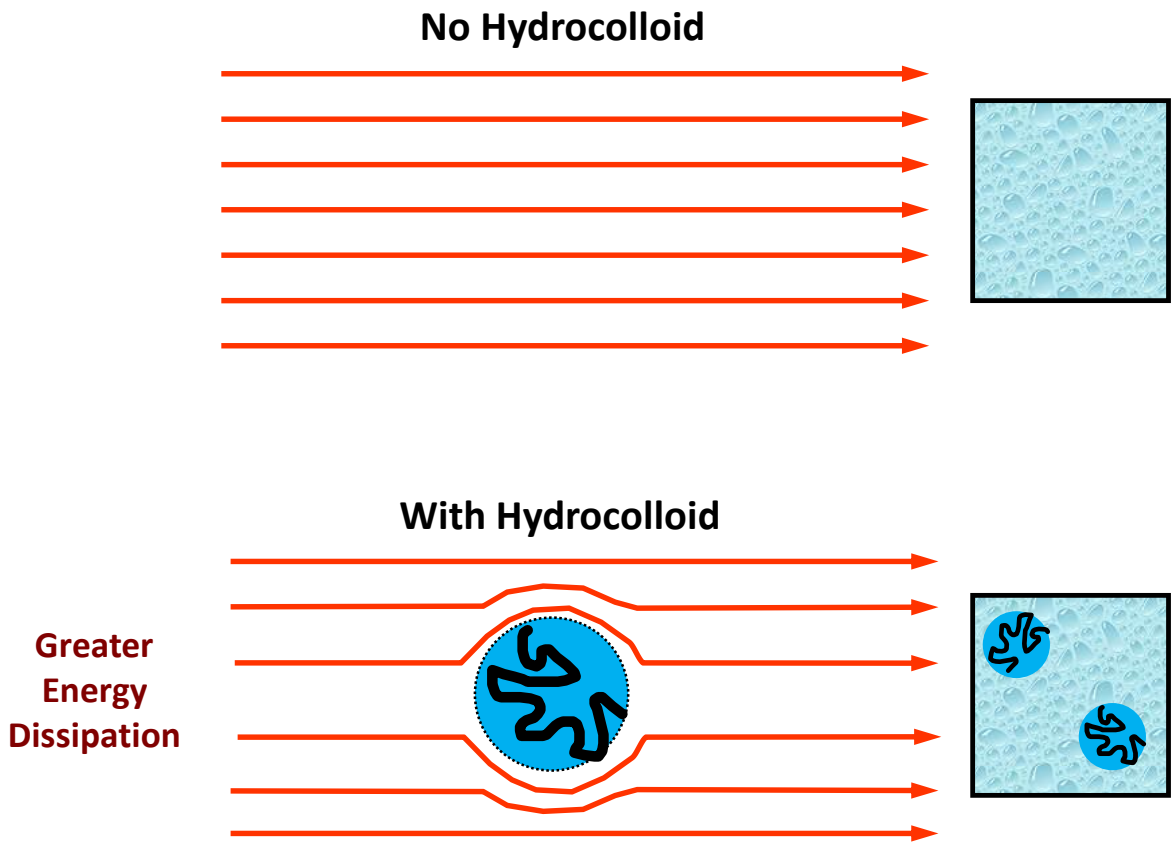


Figure 2. Hydrocolloids increase fluid viscosity by perturbing fluid flow – the fluids have a longer distance to travel in the same time, which increases the friction and energy dissipation.

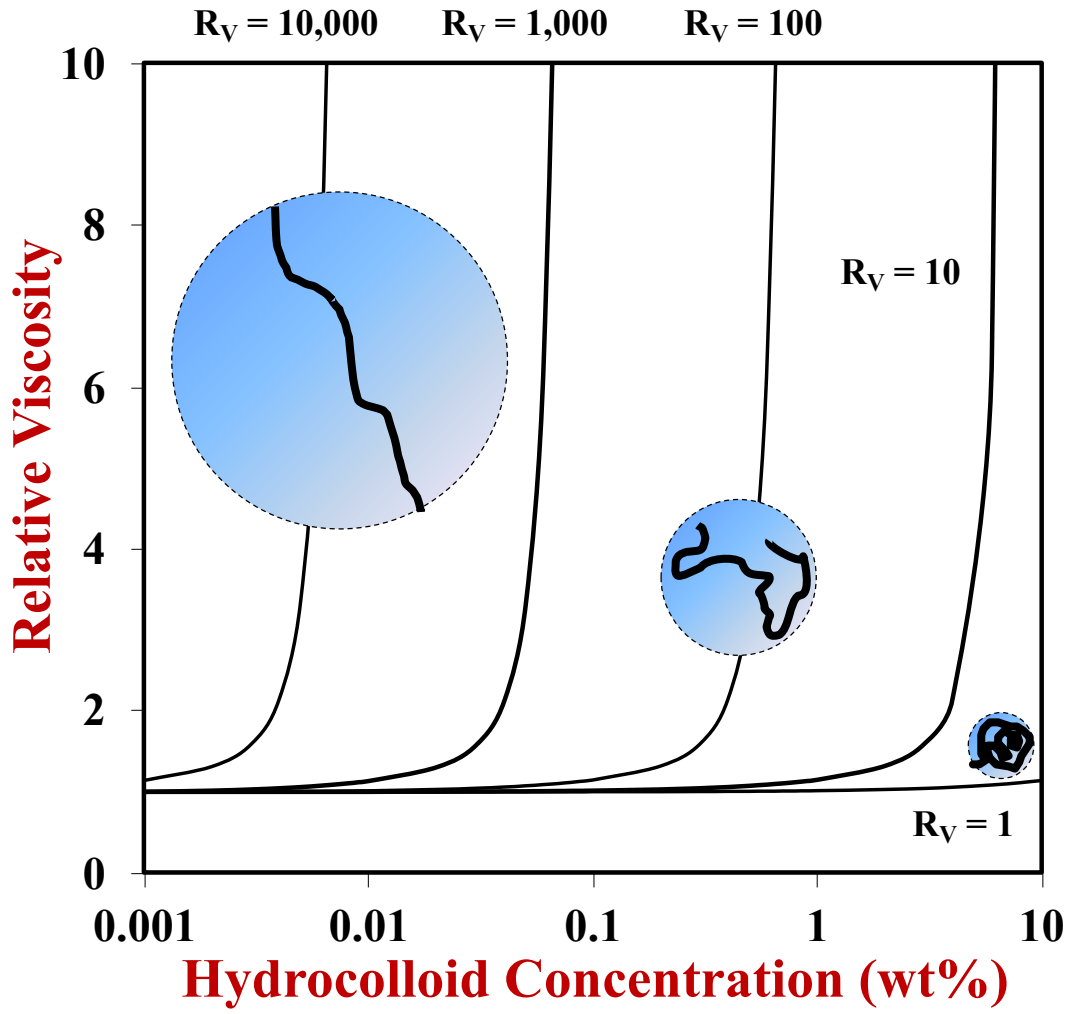


Figure 3. The ability of hydrocolloids to thicken solutions depends on their effective volume ratio, which depends on their molecular characteristics (molar mass, branching, conformation, and charge).

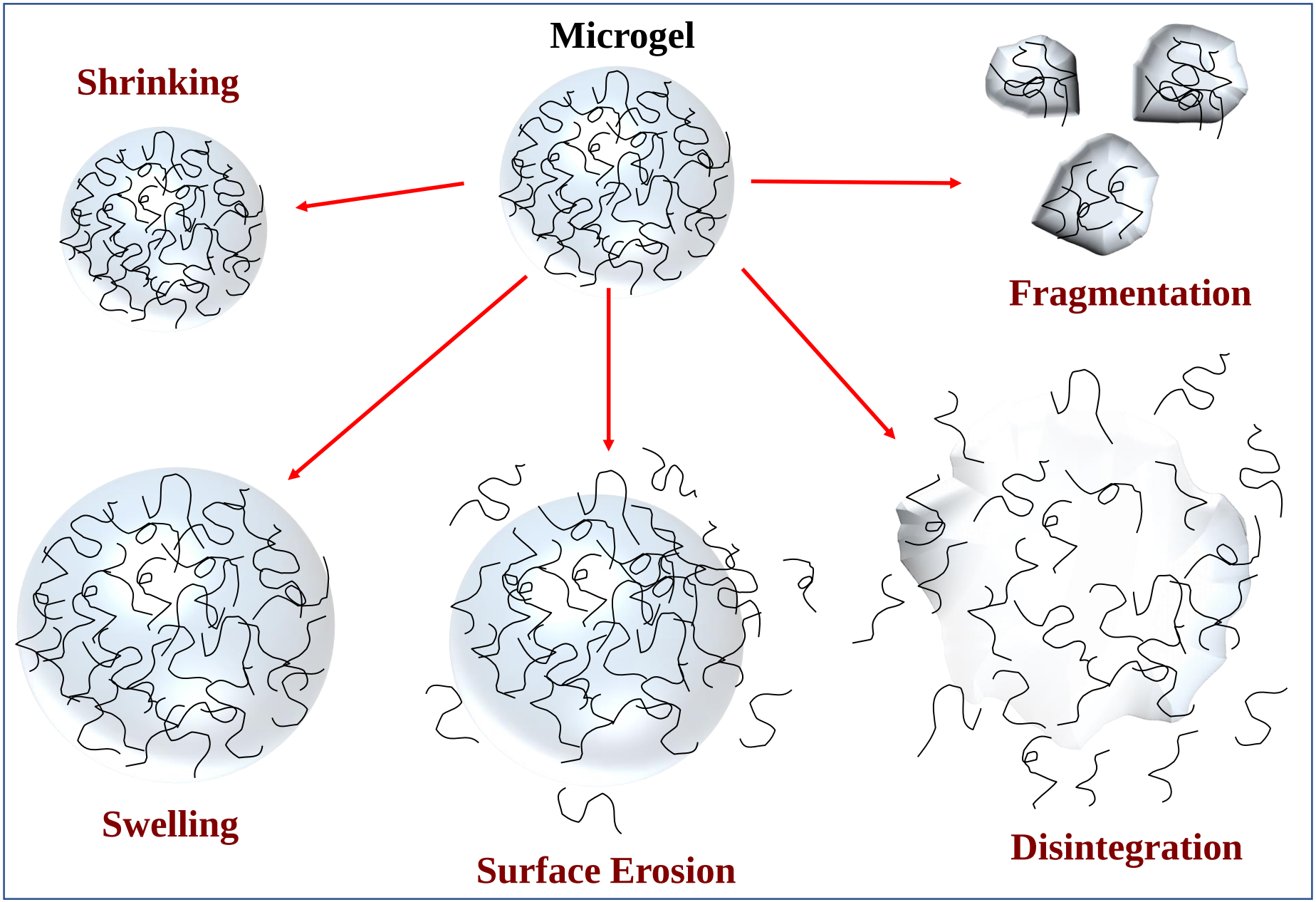
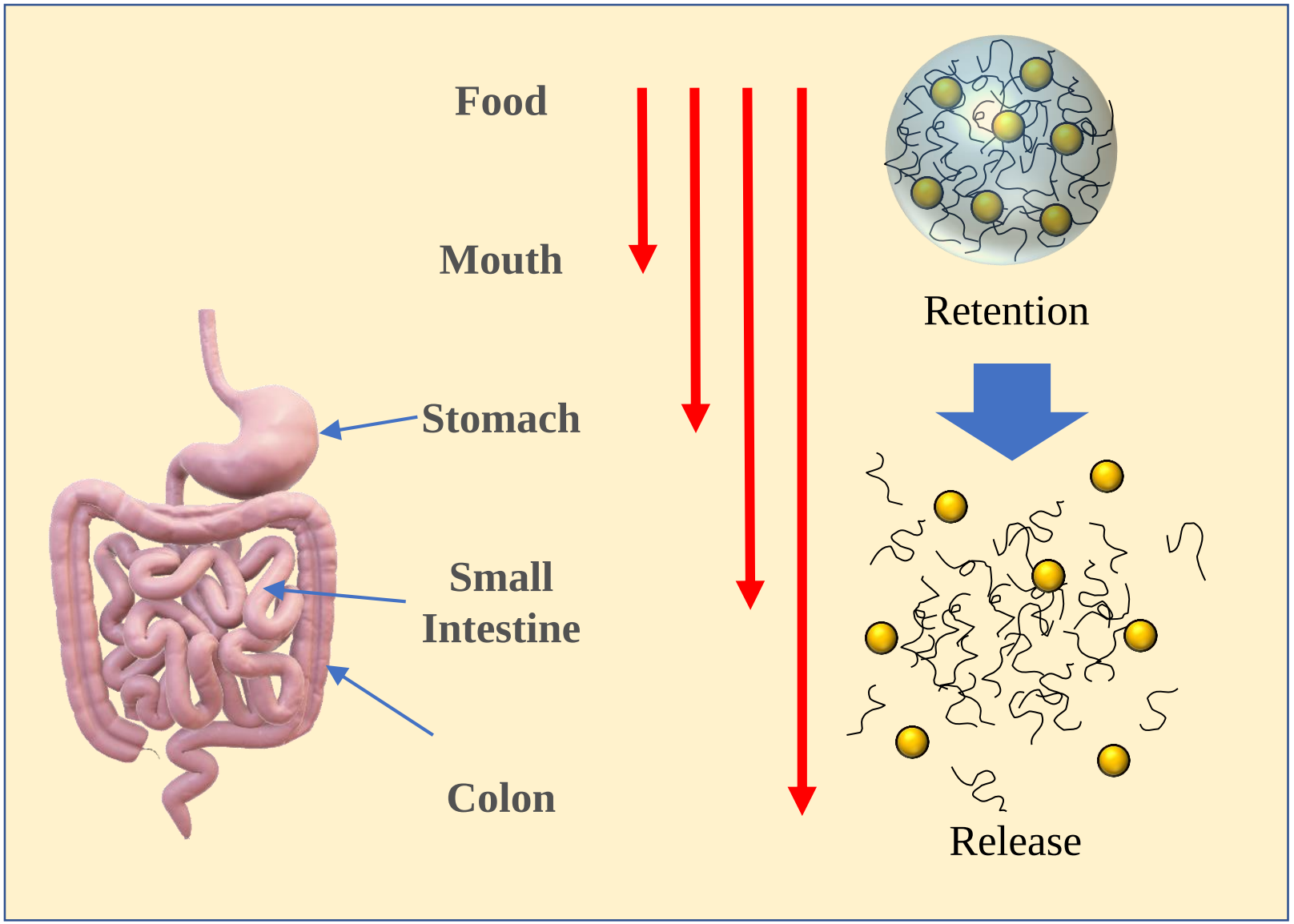


Figure 4: Hydrogel particles may breakdown in the GIT through a variety of physicochemical mechanisms, including shrinking, swelling, disintegration, erosion or fragmentation.

Figure 5: Bioactive agents can be released in different regions of the GIT by selecting biopolymers with different sensitivities to gastrointestinal conditions, such as pH, ionic strength, or enzyme activity.



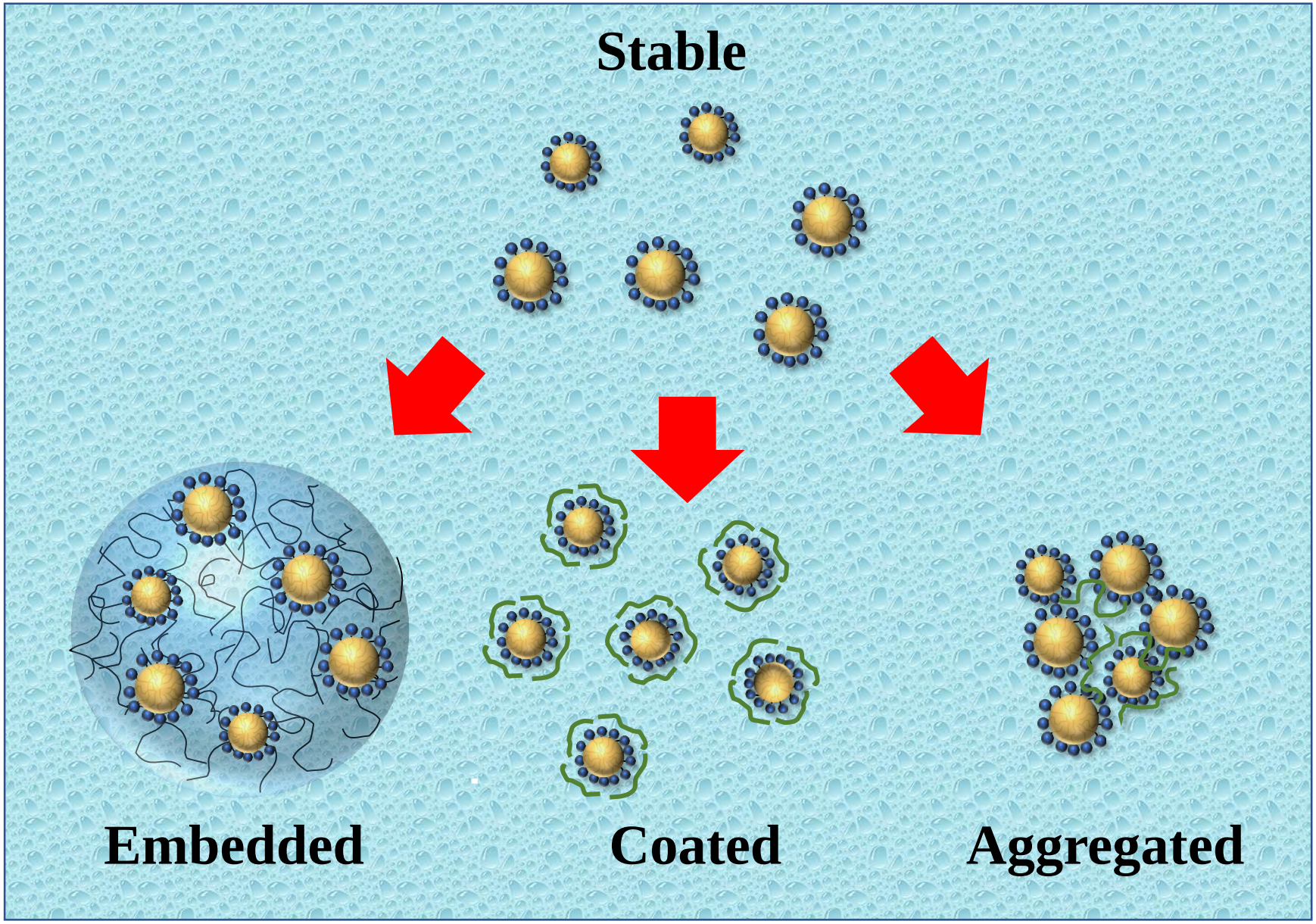


Figure 6: Hydrocolloids may impact the aggregation state or interfacial properties of macronutrients, which alters their digestion and absorption.

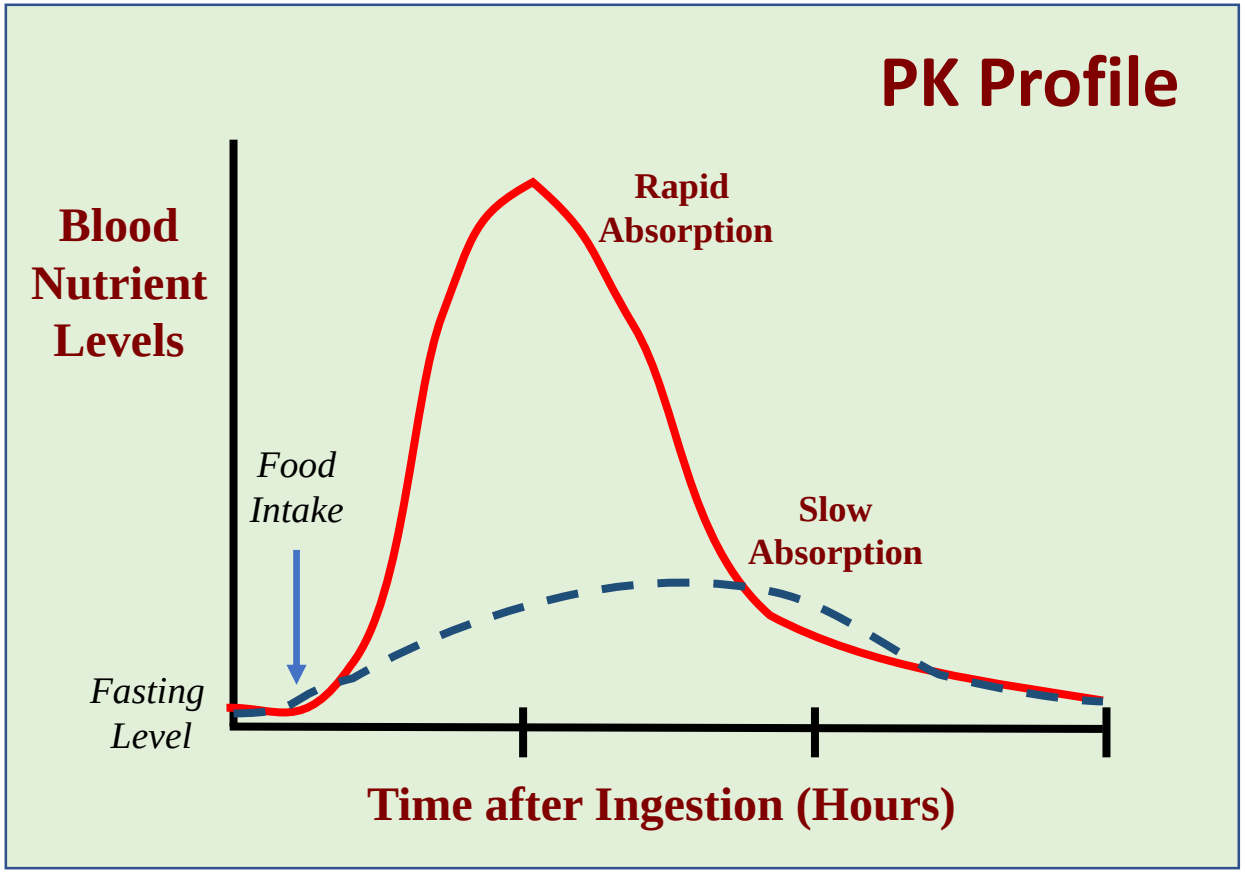


Figure 7: The pharmacokinetic (PK) profile of a bioactive component (such as a vitamin or nutraceutical) represents the change in its concentration in a specific tissue (often the bloodstream) over time.

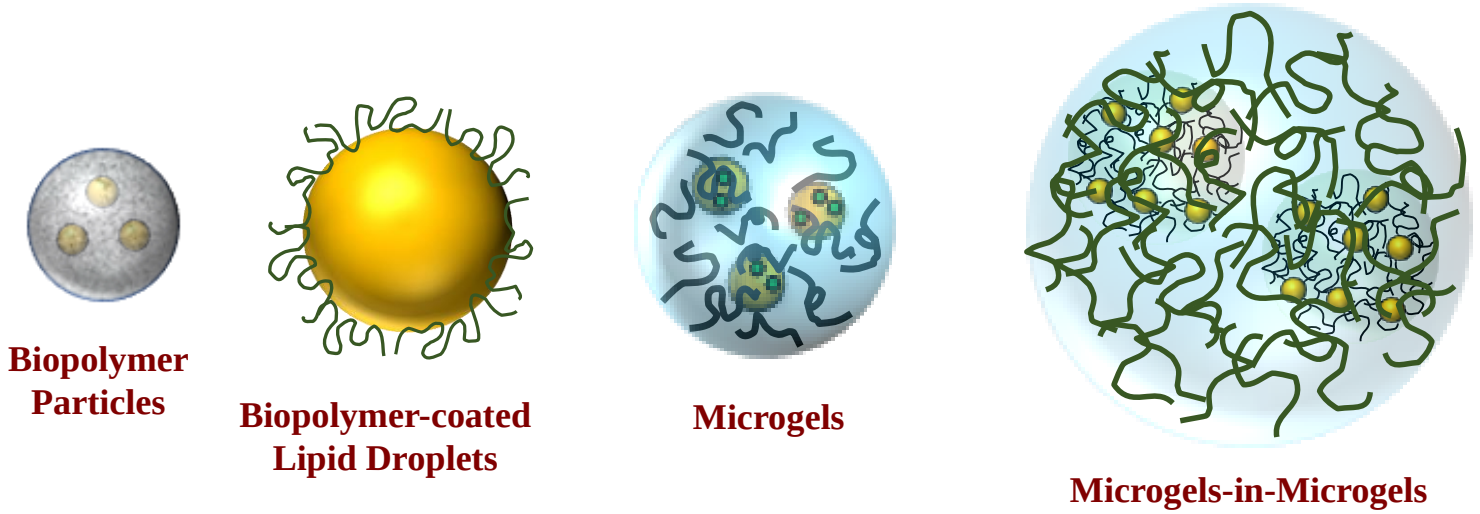


Figure 8: Examples of some kinds of colloidal delivery systems that can be prepared using hydrocolloids (not drawn to scale).

Table 1. Overview of some key molecular and functional attributes of common food-grade proteins used to as functional ingredients in foods. Here pI is the isoelectric point, and T_m is the thermal transition temperature. **Key:** *A: Type A Gelatin; B: Type B Gelatin; S: S-Type Ovalbumin; 7S and 11S Soy Glycinin fractions.* As well as the traditional functional attributes mentioned here, many can also be used as structural components of colloidal delivery systems.

Name	Source	Main Structural Type	pI	~ T_m (°C)	Solubility	Functionality
β-lactoglobulin	Milk	Globular	~ 5.0	~75	Water	Emulsifying, gelling, and foaming
Caseins	Milk	Flexible	~ 4.6	~125-140	Water	Emulsifying, gelling, and foaming
Bovine Serum Albumin	Milk/Blood	Globular	~ 4.7	~80	Water	Emulsifying, gelling, and foaming
Lactoferrin	Milk	Globular	~ 8.0	~60 & 90	Water	Emulsifying, gelling, and foaming
Ovalbumin	Egg White	Globular	~ 4.6	~74; 82^S	Water	Emulsifying, gelling, and foaming
Lysozyme	Egg White	Globular	~ 11.0	~74	Water	Emulsifying, gelling, and foaming
Phosvitin	Egg Yolk	Globular	~ 4.0	~80	Water	Emulsifying, gelling, foaming and iron binding

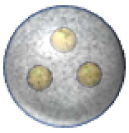
Gelatin	Animal Collagen	Flexible	~ 8 [A] ~ 5 [B]	~ 5 (fish) ~ 40 (animal)	Water	Emulsifying, gelling, and foaming
Soy Glycinin	Soybean	Globular	~ 5.0	~67^{7S}; 87^{11S}	Water	Emulsifying, gelling, and foaming
Zein	Corn	Globular	~ 6	~90	Organic Solvent	Nanoparticle formation
Pea globulins	Pea	Globular	~ 4.5	~72	Water	Emulsifying, gelling

Table 2. Summary of important molecular characteristics of some common food-grade polysaccharides used as functional ingredients in foods. As well as the traditional functional attributes mentioned here, many can also be used as structural components of colloidal delivery systems.

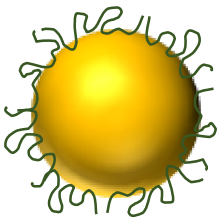
Name	Source	Main Structure Type	Major Monomer	Function
Carrageenan	Algal	Linear/Helical	Sulfated Galactan	Thickening, gelling (K^+ or Ca^{2+}), stabilizing
Xanthan Gum	*Xanthomonas campestris* exudate	Linear/Helical (High MW)	β-D-glucose (backbone)	Thickening, stabilizing, structure formation
Methyl Cellulose	Wood Pulp	Linear	Methylated Glucose	Thickening, stabilizing, gelling (thermoreversible)
Pectin	Plant Cell Walls	Highly Branched Coil	Glucuronate (backbone)	HM: Gelling (sugar + heat), stabilizing LM: Gelling (Ca^{2+}), stabilizing
Beet Pectin	Sugar Beet Pulp	Branched Coil with Protein	Glucuronate (backbone)	Emulsification, gelling (sugar + heat; Ca^{2+} or laccase), stabilizing
Gum Arabic	Acacia Sap	Branched Coil Domains on Protein Scaffold	Galactose	Emulsification, film forming
Inulin	Plants or Bacteria	Linear with occasional branches	β-D-fructose	Prebiotic, thickening

Chitosan	Crustaceans, Invertebrates	Linear	2-amino-2-deoxy-β-D-glucose	Gelling (polyphosphate)
Alginate	Algal	Linear	β-D-Mannuronic Acid	Gelling (Ca^{2+}), stabilizing
Agar	Algal	Linear	β-D-Galactopyranose	Gelling (Ca^{2+}), stabilizing
Guar gum	Seeds	Linear with side chains	D-mannose and D-galactose	Thickening, stabilizing
Locust bean gum	Seeds	Linear with side chains	D-mannose and D-galactose	Thickening, stabilizing
Tara gum	Seeds	Linear with side chains	D-mannose and D-galactose	Thickening, stabilizing

Note: *Commercially available polysaccharide ingredients typically contain appreciably different molecular and functional properties; the listed information describes general characteristics for industrial usage*.

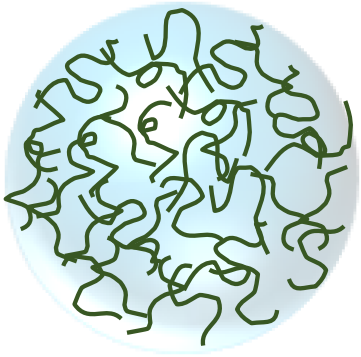


Biopolymer Particles



Biopolymer-coated Lipid Droplets

Microgels



Microgels-in-Microgels