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Graphical Abstract

**Modulation of Physicochemical Characteristics of Pickering Emulsions:
Utilization of Nanocellulose- and Nanochitin-coated Lipid Droplet Blends**

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ABSTRACT

Mixed Pickering emulsions were prepared by blending anionic nanocellulose-stabilized lipid droplets with cationic nanochitin-stabilized lipid droplets. Changes in the surface potential, particle size, shear viscosity, and morphology of the mixed emulsions were characterized when the droplet mixing ratio was varied. Emulsion properties could be tailored by altering the pH and mixing ratio. Surface potential measurements suggested that the nanochitin-coated lipid droplets adsorbed to the surfaces of the nanocellulose-coated lipid droplets, thereby dominating the overall electrical characteristics of the mixed emulsions. As a result, the mixed emulsions had better stability to coalescence than the single emulsions containing only nanocellulose-coated lipid droplets. Our results suggest that the physicochemical properties, shelf-life, and functional performance of Pickering emulsions may be modulated by blending different kinds of particle-stabilized lipid droplets together.

Keywords: Pickering emulsions; heteroaggregation; nanochitin; nanocellulose; nanoparticles

INTRODUCTION

Oil-in-water emulsions consist of small oil droplets suspended within water¹. From a thermodynamic perspective, emulsions are unstable systems due to the density contrast and interfacial tension between the oil and water phases.¹ Consequently, stabilizers such as emulsifiers and thickeners, have to be added to increase their kinetic stability and make them suitable for commercial applications. Most emulsifiers currently used in the food industry are surface-active molecules that adsorb to oil droplet surfaces and inhibit their aggregation by generating a repulsive force between them.^{2, 3} Numerous kinds of natural and synthetic molecular emulsifiers are available for utilization in foods and beverages, including phospholipids, polypeptides, polysaccharides, and biosurfactants.^{4, 5} More recently, researchers have focused on the potential of particle-based emulsifiers to form Pickering emulsions suitable for application in the food industry.⁶⁻⁸ Colloidal particles with appropriate wetting characteristics adsorb strongly to oil droplet surfaces and form a protective coating that greatly increases their resistance to coalescence.⁹ Various types of edible colloidal particles have already been shown to be suitable for this purpose.^{10, 11}

In this study, we focused on two types of nature-derived solid nanoparticles capable of stabilizing Pickering emulsions: nanocellulose and nanochitin. Nanocellulose is produced from cellulose fibers, which are a natural, sustainable, and abundant biomaterial.¹²⁻¹⁴ Numerous studies have reported that nanocellulose can be successfully used to form and stabilize Pickering emulsions.^{15, 16} Indeed, nanocellulose has been shown to be highly effective at inhibiting the coalescence of oil droplets.¹⁷⁻¹⁹ This phenomenon is due to the ability of nanocellulose fibers to strongly adsorb to the oil droplet surfaces and create a thick viscoelastic gel-like coating.^{16, 17}

The functional performance of nanocellulose can also be extended by carrying out chemical²⁰ or enzymatic²¹ modifications.

Chitin is a naturally abundant polysaccharide typically isolated commercially from crustacean shells, which is reported to be nontoxic, biocompatible, and biodegradable.^{12, 22-25} Chemically, it consists of a linear polysaccharide chain comprised of repeating units of β -(1 $\rightarrow$ 4)-N-acetyl-d-glucosamine. Many researchers have explored the potential applications of chitin as a functional biomaterial.²⁴ Recently, attention has been directed towards the development and utilization of chitin nanomaterials, such as chitin nanocrystals and nanofibers.^{24, 26, 27} Chitin nanocrystals are usually produced industrially by carrying out an acid hydrolysis of shrimp shells, while chitin nanofibrils are prepared by applying mechanical forces to promote disintegration.^{28, 29} Different processing treatments result in the generation of chitin nanomaterials with different physiochemical and functional properties²⁵. For example, emulsions stabilized by chitin nanofibrils have been reported to have higher viscosities and better thermal stabilities than those stabilized by chitin nanocrystals.²⁴ Moreover, the thermal stability of nanochitin-coated oil droplets has been reported to be much better than nanocellulose-coated ones.²⁶ These studies indicate suggest that nanochitin has promising applications to form and stabilize Pickering emulsions.

In the present study, the potential of extending the functionality of particle stabilizers by creating mixed Pickering emulsion systems was investigated. In particular, we hypothesized that the physicochemical properties and stability of mixed emulsions could be controlled by altering the ratio of different types of droplets present. The mixed Pickering emulsions were formed by blending nanocellulose-coated oil droplets with nanochitin-coated oil droplets in different ratios. These two types of particle emulsifier were examined because they have opposite surface

charges: nanochitin is positive over most pH values found in food, whereas nanocellulose is negative. As a result, the different kinds of particle-coated oil droplets would be expected to be attracted to each other through electrostatic forces. There has been little previous work on mixed Pickering emulsions, and so, our study should provide some valuable information that may increase the utilization of nanoparticle-based emulsifiers in the food industry. Researchers have formed Pickering emulsions by mixing different kinds of inorganic colloidal particles together to form mixed interfaces, such as SiO₂ and Fe₃O₄ nanoparticles³⁰ or silica and titania nanoparticles³¹. To the authors knowledge, however, systems formed by mixing two different kinds of edible Pickering emulsions together have not been examined previously.

MATERIALS AND METHODS

Materials

Nanocellulose (NC) was prepared from birch tree fibers as described previously.³² Fiber disintegration was achieved by passing them six-times through a high-pressure microfluidizer (M110P, Microfluidics Int. Co., Newton, MA). The average width of this nanocellulose was recently reported to be $\sim 20 \pm 8$ nm.³³ The mean particle diameter measured by static light scattering was found to be 18.6 ± 1.2 μ m. It should be noted that the mathematical model used to analyze the diffraction pattern in the light scattering instrument assumes that the particles are spherical, and so this value should be treated with caution.

Several steps were used to prepare the nanochitin (NCh), which have been described in a recent study²⁶. Briefly, chitin was first isolated from fresh crab shells (*Callinectes sapidus*) purchased from a fish market in Finland (Helsinki Harbor, Finland). The isolated sample was then treated with concentrated alkaline solution (33 w/w% NaOH solution) for 3.5 hours at 90 °C

to partially deacetylate it, resulting in a degree of deacetylation (DD) of 27.3%. The deacetylated chitin (DE-chitin) was then washed, dried, and stored at 4 °C. The DE-chitin was then dissolved in acetic acid solution (pH = 3), and nanochitin was obtained by sonicating for 40 mins (FB505, Fisher Scientific, USA; 50% power, 3s on/2s off). The mean particle diameter of a nanochitin suspension measured by laser diffraction was $0.220 \pm 0.002 \mu\text{m}$, which should again be treated with caution for the reasons discussed for nanocellulose. Samples of both nanocellulose and nanochitin were kept at 4 °C before use.

Corn oil was purchased from a local store (Mazola, ACH Food Company, Memphis, TN). Nile red (a fat-soluble fluorescent dye) was purchased from Sigma-Aldrich Chemical Co. (St. Louis, Mo, USA). The other reagents used in the experiments were analytical grade and obtained from Sigma-Aldrich or Fisher Scientific (Hampton, NH, USA). Double distilled water was employed for all experiments.

Preparation of Pickering emulsions

The water phases used to formulate the Pickering emulsions were prepared by dispersing nanoparticles (nanocellulose or nanochitin) into double distilled water to reach a level of 0.3 wt%. Pure corn oil was used as the oil phase to formulate the Pickering emulsions. The water phase (90 wt%) and oil phase (10 wt%) were pre-mixed with a high-shear mixer (Bamix, BiospecProducts, Bartlesville, OK) for 2 mins at room temperature. Pickering emulsions were then produced by sonicating for 4 mins (FB505, Fisher Scientific, USA) inside an ice-water bath, using a power level of 50% strength and 3s/2s on/off cycles.

Preparation of mixed Pickering emulsions

Nanochitin-stabilized emulsions were added to nanocellulose-stabilized emulsions in a glass beaker with continuous stirring. Mixed Pickering emulsions were prepared by blending varying

mass ratios of the two different emulsions: 1:0, 1:0.5, 1:1, 1:2, 0:1 NC:NCh. These values correspond to mixed emulsions containing 0%, 33.3%, 50%, 66.7%, and 100% nanochitin. The pure nanocellulose, pure nanochitin, and mixed emulsions were then kept under ambient conditions for 24 hours prior to analysis.

Storage stability of Pickering emulsions

The Pickering emulsions were transferred into clean and sterile plastic test tubes, and then stored under ambient conditions for 20 days.

Particle size and charge: The pH of the Pickering emulsions was determined with a digital pH meter (Table 1). Then, the Pickering emulsions were diluted with pH-adjusted double distilled water (same pH as measured sample) before measuring the size and charge of the particles. A laser diffraction instrument was used to determine the mean particle diameter and particle size distribution of the Pickering emulsions (Mastersizer 2000, Malvern Instruments, Worcestershire, United Kingdom). The samples were stirred at 12,000 rpm during the measurements to ensure they were homogeneous. The particle size is given as the volume-weighted mean particle diameter (d_{43}).

Table 1. pH values of Pickering emulsions prepared with various mixing ratios of nanocellulose (NC)- and nanochitin (NCh)-coated lipid droplets.

	NC	NC/NCh = 1/0.5	NC/NCh = 1/1	NC/NCh = 1/2	NCh
pH	6.6	3.0	3.0	3.0	2.9

Particle electrophoresis was used to measure the surface charge (ζ -potential) of the particles within the Pickering emulsions (Nano-ZS, Malvern instruments, Worcestershire, United

Kingsom). Prior to analysis, the emulsions were diluted with pH-adjusted distilled water to be in the optimum intensity range to carry out particle charge measurements.

Shear viscosity: The rheological properties of the Pickering emulsions were characterized by dynamic shear rheometry (Kinexus, Malvern, Worcestershire, UK). The measurement cell used had a concentric cylinder geometry (25 mm internal and 27 mm external). The emulsions were poured or gently scooped into the measurement cell and then incubated at 25°C for 5 min before analysis to allow them to reach the measurement temperature. The shear stress-shear rate relationship was then recorded over the range from 0.1 to 100 s⁻¹ with 15 mins total measurement time per sample. The apparent shear viscosity was then calculated at each shear rate from these measurements.

Microstructure: The morphology of the Pickering emulsions was assessed using both electron and optical microscopy. For electron microscopy, the Pickering emulsions were diluted with distilled water 10-fold. Then, small aliquots (10 µL) of the diluted emulsions were placed on copper grids (400 mesh, carbon film, CF400-CU, Electron Microscope Sciences), and held for 2 mins. Afterwards, filter paper was used to absorb any excess sample. 10 µL of phosphotungstic acid solution (PTA, 1 %) was then placed on the copper grids as a negative stain for 2 mins, and then any remaining dye was soaked up with filter paper. Afterward, the copper grids were washed 3-times with distilled water then air-dried for 24 hours. Transmission electron microscopy (TEM) was then utilized to observe the morphology of the Pickering emulsions (JEOL JEM-2000FX).

The microstructures of the Pickering emulsions were also examined using optical and confocal laser scanning microscopy with a 40×objective lens (Nikon D-Eclipse C1 80i, Nikon, NY, United States). The Pickering emulsions were first stained with an oil-soluble dye (1

mg/mL Nile Red), then small aliquots (5 μ L) of the stained emulsions were placed on the glass microscope slides and covered with a glass slip to avoid evaporation.

RESULTS AND DISCUSSION

Properties of Nanocellulose and Nanochitin emulsions

The physicochemical and structural properties of the initial nanocellulose- and nanochitin-emulsions were analyzed (Figs. 1 to 3).

Particle size and charge characteristics

Figure 1: Particle size distribution, mean particle diameter, and surface potential of oil-in-water Pickering emulsions stabilized by either nanocellulose or nanochitin.

Figure 1 shows the initial particle size characteristics of the Pickering emulsions determined by laser diffraction were considerably different. The nanocellulose-emulsions contained considerably larger particles ($d_{43} = 14.3 \mu\text{m}$) than the nanochitin-emulsions ($d_{43} = 1.68 \mu\text{m}$).

Additionally, the particle size distribution was much broader for the nanocellulose-emulsions (1 to 100 μm) than the nanochitin-emulsions (0.5 to 5 μm).

The ζ -potential measured for the nanocellulose-emulsions was -41.3 ± 0.3 mV (pH 6.6), while the value in the nanochitin emulsions was $+46.6 \pm 1.2$ mV (at pH 2.9). As discussed later, the two emulsions had to be prepared at different pH values so that they were both physically stable, *i.e.*, extensive droplet aggregation was avoided. Moreover, the two emulsions contained oppositely charged particles of fairly similar charge magnitude at these pH values, which is an advantage when trying to promote droplet aggregation through electrostatic attractive forces.

Figure 2. The effects of pH on the ζ -potential (a) and mean particle diameter (b) of nanocellulose- and nanochitin-emulsions.

The pH-dependence of the physicochemical properties and structures of nanocellulose- and nanochitin-emulsions was then determined (Fig. 2). The particles in the nanocellulose-emulsions were highly negative from pH 8 to 5, but became less negative from pH 5 to 3, and eventually

became slightly positive at pH 2 (Fig. 2a). The anionic nature of the composite particles in these emulsions is a result of charged sulfate and carboxyl groups on nanocellulose³⁴. Sulfate groups keep their strong negative character across the entire pH range used in our study because of their low pK_a values ($< \text{pH } 2$), whereas the charge of carboxylic groups varies with pH because they have pK_a values around pH 3.5³⁴. Consequently, at relatively high pH values they are negatively charged ($-\text{COO}^-$) but at lower values they lose their charge ($-\text{COOH}$). The surface potential of the nanochitin-emulsions was strongly positive from pH 2 to 6, but became highly negative at higher pH values (Fig. 2a). The strong positive charge under acidic conditions is a result of protonation of the amino groups ($-\text{NH}_3^+$). The fact that there was also a charge at higher pH values suggests that there were also some ionizable anionic groups on the nanochitin, such as carboxyl groups ($-\text{COO}^-$). Previous researchers have also reported that the charge on chitin nanoparticles goes from cationic to anionic as the pH is raised³⁴. In that study, the presence of carboxyl groups was attributed to the chemical treatment of the nanochitin during the bleaching process. It should be noted that the nanochitin was strongly aggregated at the higher pH values, forming visibly large clumps, and therefore the particle electrophoresis measurements should be used with some caution.

The particle size of the two emulsions, which is influenced by any droplet aggregation that has occurred, also depended strongly on solution pH (Fig. 2b). For the nanocellulose-emulsions, the particle size was relatively large from pH 2 to 4, decreased at pH 5, then became relatively small from pH 6 to 10. This phenomenon arises from changes in the electrostatic forces operating amongst the droplets in the Pickering emulsions. At relatively low pH values ($\text{pH} < 5$), the electrostatic repulsion amongst nanocellulose-coated oil droplets is relatively weak, leading to widespread droplet aggregation. Conversely, at higher pH values the electrostatic

repulsion amongst the anionic droplets is relatively strong, which inhibits aggregation. For the nanochitin-emulsions, the opposite effect was observed (Fig. 2b). The emulsions contained relatively small particles from pH 2 to 4, but much larger ones at higher pH values. In this case, there was a strong electrostatic repulsion between the positively charged nanochitin-coated oil droplets at low pH values, which would have prevented them from aggregating. At higher pH values, there may only have been a weak electrostatic repulsion amongst the droplets, which was not sufficiently high to inhibit aggregation. Alternatively, there may have been both positive (-NH_3^+) and negative (-COO^-) groups on the surfaces of the nanochitin-coated oil droplets at higher pH values, which promoted droplet aggregation due to electrostatic attraction. These results clearly show that solution pH profoundly influences the stability of both types of Pickering emulsion, which may limit their application in many foods and other commercial products.

Microstructure Analysis

Figure 3. Transmission electron microscopy images of nanocellulose-emulsions (left) and nanochitin-emulsions (right). Some distinctive structures observed in the images are highlighted with white arrows.

The TEM images indicate the oil droplets within the nanocellulose-emulsions were coated by nanocellulose fibers, as well as being trapped within a gel network consisting of overlapping nanocellulose fibers in the surrounding aqueous phase (Fig. 3). The nanochitin-emulsions had a quite different microstructure. They appeared to contain relatively large oil droplets surrounded by approximately spherical nanochitin particles. Interestingly, the individual oil droplets within the nanocellulose-emulsions appeared to be quite small ($< 5 \mu\text{m}$), suggesting that the large particle sizes determined using the laser diffraction method (Fig. 1) may have been due to the nanocellulose fibers, rather than the oil droplets.

Structural and physicochemical characteristics of mixed Pickering emulsions

The impact of mixing the anionic nanocellulose-emulsions with the cationic nanochitin-emulsions on their physicochemical and structural properties was then investigated.

Particle size and surface charge: The characteristics of the particles within the mixed nanocellulose- and nanochitin-emulsions was strongly influenced by the ratio of positive-to-negative droplets they contained (Figure 4). The mean particle diameter initially increased when the level of cationic droplets was raised from 0 to 33.3%, but then it decreased when their level was further raised from 33.3 to 100%. The initial increase in particle size might be attributed to hetero-aggregation, *i.e.*, the electrostatic attraction between positively and negatively charged droplets. Interestingly, however, the particles in the mixed emulsions were smaller than those in the two individual emulsions at higher levels of nanochitin-coated droplets. This result suggests that some other physicochemical phenomenon was occurring in these systems. For this reason, surface potential measurements were carried out to provide some insights into this effect.

Figure 4. The particle size distributions, mean particle diameters, ζ -potentials, and appearances of mixtures of nanocellulose- and nanochitin-emulsions.

Surface potential analysis showed that the electrical charge on the particles was dominated by that of the nanochitin-droplets in all of the mixed systems (Fig. 4). This suggests that the smaller cationic nanochitin-coated oil droplets may have formed a layer around the larger anionic nanocellulose-coated oil droplets. The ζ -potential values determined by the electrophoresis instrument used in the current study are mainly determined by the electrical characteristics of the outer edges of particles. Consequently, an outer layer of cationic droplets would make the overall charge of the composite particles in the system positive. In addition, the

adsorption of the smaller cationic droplets around the larger anionic ones may have promoted some disruption of the aggregates in the nanocellulose-emulsions.

Viscosity

Figure 5. Impact of mixing ratio on the viscosity of mixed nanocellulose- and nanochitin-emulsions: (A) apparent viscosity *versus* shear rate; (B) apparent viscosity *versus* percentage of cationic nanochitin-coated droplets present (shear rate = $10 s^{-1}$).

The rheology of the mixed emulsions was characterized using shear rheometry (Fig. 5). Initially, the rheology of the individual nanocellulose- and nanochitin emulsions is compared. Both emulsions displayed shear thinning, *i.e.*, a decrease in apparent viscosity when the shear rate was raised. This effect, however, was much more pronounced in the nanocellulose-emulsions than in the nanochitin-emulsions. The magnitude of the apparent shear viscosity was much higher in the nanocellulose-emulsions than in the nanochitin-ones. This difference may be

because the nanocellulose-emulsions contained highly flocculated oil droplets, as well as a network of interlinked nanocellulose fibers in the surrounding continuous phase (Fig. 3). Flocculated droplets or nanofibers disturb the fluid flow in the emulsions, thereby leading to more energy dissipation due to friction, and a higher shear viscosity. Conversely, the nanochitin-emulsions appeared to contain individual oil droplets and did not contain a network of nanochitin particles in the aqueous phase (Fig. 3). The pronounced shear thinning behavior observed in the nanocellulose-emulsions may therefore have been due to deformation and disruption of the flocs, as well as alignment of the nanofibers with the flow field.

The mixed emulsions containing 33.3% nanochitin-coated droplets had a slightly higher apparent shear viscosity than the ones containing none of these droplets (Fig. 5). This effect may have been because low levels of cationic droplets promoted some additional aggregation of the anionic droplets due to the hetero-aggregation mechanism mentioned earlier. As the level of nanochitin-coated droplets was further increased, there was a decrease in the apparent shear viscosity. This may have been because the cationic oil droplets formed a layer around the anionic ones, thereby reducing their tendency to form large aggregates. In particular, the nanofibers used in this study may have impacted the stability and rheology of the Pickering emulsions by altering the mechanical properties of the coatings around the oil droplets. Previous researchers have studied the impact of the adsorption of nanochitin and nanocellulose on the properties of oil-water interfaces.^{26, 35} They showed that the adsorption of the nanofibers increased the interfacial elasticity, which may have increased the resistance of the nanofiber-coated oil droplets to coalescence or flocculation. Overall, our results show that Pickering emulsions with different rheological characteristics can be prepared by blending positive and negative droplets together in different ratios.

Storage stability of mixed Pickering emulsions

The physical stability of emulsions determines their shelf life. For this reason, the physicochemical properties of the Pickering emulsions were characterized after 0 or 20 days storage at ambient temperature (Figs. 6 and 7). The relative increase in mean particle diameter after storage was used as an indicator of emulsion stability:

$$\%Size\ Increase = 100 \times \frac{(d_{end} - d_{start})}{d_{start}}$$

Here, d_{end} and d_{start} are the mean particle diameters at the end and start of the storage period.

Initially, the stability of the individual Pickering emulsions was compared. The size of the particles in the nanocellulose-emulsions increased substantially after storage (Figs. 6A and 6B), which was mainly caused by coalescence of the oil droplets, as demonstrated by the increase in the size of the individual oil droplets seen in the microscopy images (Figs. 7 and 8). In contrast, only a small increase was observed in the size of the particles in the nanochitin-emulsions after storage, which was consistent with the microscopy images (few aggregated droplets). These results indicate that the nanochitin is much better at inhibiting droplet coalescence than the nanocellulose under the conditions used in this study. Interestingly, the apparent shear viscosity of the nanocellulose-emulsions was substantially lower after storage, but was significantly higher in the nanochitin-emulsions (albeit with a large variation between samples) (Fig. 6C). The observed viscosity decrease in the nanocellulose-emulsions may have been due to a reduction in the interfacial area of the oil droplets (resulting from the increase in droplet size), so there were less sites available for the nanocellulose fibers to bind to. Conversely, the viscosity increase in the nanochitin-emulsions may have been due to increased droplet aggregation during storage, possibly due to rearrangement of the nanoparticles in the system. For instance, a chitin

nanoparticle may have originally been attached to the surface of a single oil droplet but over time it may have become attached to the surfaces of two or more different droplets, thereby promoting bridging flocculation.

Figure 6. The particle size distribution (A), %increase in droplet size (B), and %increase in viscosity (C) of mixed emulsions after 20 days storage. Some of the particle size distribution data has been shifted up the y-axis to better compare the different samples.

In the mixed emulsions containing 33.3% nanochitosan-coated droplets, the mean particle size decreased slightly during storage, suggesting that there may have been some structural rearrangements in the system. For all the other mixed emulsions, the measured particle size remained fairly constant throughout storage, suggesting the presence of nanochitin-coated droplets improved the stability of the system. Moreover, the apparent viscosity of all the mixed Pickering emulsions only increased slightly after storage (Fig. 6C), suggesting that they were relatively stable.

Figure 7a. Optical microscopy images of nanocellulose- and nanochitin-emulsions, as well as their mixtures. The scale bar represents 20 μm.

Figure 7b. Confocal fluorescence microscopy images of nanocellulose- and nanochitin-emulsions, as well as their mixtures. The oil phase was dyed red using Nile red. The scale bar represents 50 μm .

Interaction mechanism

Finally, based on our experimental observations and knowledge of colloidal dispersions, we proposed a possible mechanism of interaction for the mixed Pickering emulsions (Fig. 8).

Figure 8. Schematic illustration of 1:1 mixed nanocellulose- and nanochitin-emulsions, where the confocal image is from the white box in Figure 7.

During homogenization, nanocellulose was less effective at generating fine oil droplets than nanochitin, which may have been because it consisted of long fibers, whereas the nanochitin consisted of small spheroids. The small nanochitin particles may therefore have moved to the oil droplet surfaces formed as a result of homogenization more rapidly. Moreover, the nanocellulose formed a network of interlinked fibers within the continuous phase of the emulsions, which may have contributed to their relatively high viscosity. This high viscosity may also have interfered with droplet disruption within the homogenizer, leading to the presence of relatively large oil droplets.

When low levels of nanochitin-coated droplets (33.3%) were mixed with high levels of nanocellulose-coated droplets (66.7%), some bridging flocculation occurred. In other words, the small cationic droplets formed electrostatic bridges between the anionic droplets. However, at higher levels of nanochitin-coated droplets ($\geq 50\%$), the small cationic droplets formed a shell around the larger anionic droplets, which reduced the particle size and the viscosity, as well as increasing the coalescence stability.

Overall, our results show that Pickering emulsions properties can be controlled by varying the ratio of cationic and anionic droplets they contain. This knowledge may prove valuable for designing food products with novel rheological or stability characteristics. For instance, it may be possible to create reduced-calorie or slowly digestible pastes, spreads, dressings, or sauces with novel textures.

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