Pickering Emulsions Stabilized by Mesoporous Nanoparticles with Different Morphologies in Combination with DTAB

Danhua Xie, Yulong Jiang, Kangling Li, Xinyue Yang, and Yunjin Zhang

ABSTRACT: The morphology of nanoparticles plays a significant role in the properties and applications of Pickering emulsions. Oil-in-water (O/W) Pickering emulsions were prepared using spherical, rod-like, and thread-like mesoporous silica nanoparticles (MSNPs) in combination with the cationic surfactant dodecyltrimethylammonium bromide (DTAB) as a stabilizer. The effects of nanoparticle morphology on the stability and stimuli-responsive properties of Pickering emulsions were investigated. For spherical and rod-like MSNP systems, stable Pickering emulsions were obtained at DTAB concentrations above 0.2 mmol·L⁻¹. Stable Pickering emulsions containing thread-like MSNPs were produced at lower DTAB concentrations of approximately 0.1 mmol·L⁻¹. The droplets with thread-like MSNPs were extremely large with an average diameter around 700 μm at DTAB concentrations of 0.1−0.3 mmol·L⁻¹, which were approximately 20 times larger than those of conventional droplets. Scanning electron microscopy (SEM) images showed that all three types of MSNPs were located at the O/W interfaces. Irrespective of the morphology of the MSNPs, all the stable Pickering emulsions retained their original appearance for more than 6 months. By adding NaOH and HCl alternatively, the Pickering emulsions containing spherical and rod-like MSNPs could be switched between unstable and stable states more than 60 times. The Pickering emulsions containing thread-like MSNPs, by contrast, could have their droplet size switched between large and small more than 10 times without any obvious phase separation. The high anisotropy of thread-like MSNPs contributed to the low interface curvature of the droplets. This study revealed the relationship between the morphology of MSNPs and the characteristics of Pickering emulsions. These results enrich our knowledge about the formulation of Pickering emulsions and expand their applications.

1. INTRODUCTION

An emulsion is a thermodynamically unstable system consisting of two immiscible liquids, one of which is dispersed in the other. Besides surfactants, amphiphilic solid nanoparticles can also be adsorbed at liquid−liquid interfaces to lower the interfacial surface energy and prevent the coalescence of emulsion droplets. Emulsions stabilized by nanoparticles are known as Pickering emulsions. These emulsions are widely used in many fields including food science, biomedicine, and catalysis and in the manufacture of cosmetics and functional materials. Compared with traditional emulsions stabilized by surfactants or polymers, Pickering emulsions possess various advantages, such as increased stability, lower toxicity, and additional characteristics derived from the properties of the particles themselves.\(^\text{1,4,10,11}\)

The morphological properties of nanoparticles, such as size, shape, anisotropy, surface roughness, and specific surface area, play a critical role in the properties and behavior of Pickering emulsions. Binks compared the average droplet diameters of oil-in-water (O/W) emulsions stabilized by hydrophilic silica nanoparticles.\(^\text{18}\) With increasing nanoparticle size, the droplet diameters also increased. The droplets also evolved from being spherically shaped to being nonspherical. O/W Pickering emulsions stabilized by cylindrical polystyrene nanoparticles were stable for up to 1 year over a wide pH range. In contrast, obvious coalescence occurred after several days in Pickering emulsions prepared using spherical polystyrene nanoparticles.\(^\text{19}\) Anisotropic (rod-shaped or disc-like) nanoparticles had a higher detachment energy than that of spherical nanoparticles, indicating that the former can be adsorbed at liquid interfaces more strongly.\(^\text{20,21}\) Huang et al. investigated O/W Pickering emulsions stabilized by silica microrods with various aspect ratios (ARs) from 1 to 16.\(^\text{22}\) The results showed that the properties of Pickering emulsions were highly dependent on the ARs of the nanoparticles. The larger the AR, the more stable the emulsion. The enhanced stability
was the result of a higher steric hindrance, greater interfacial adsorption energy, and stronger capillary forces. Bose and co-workers reported O/W Pickering emulsions stabilized by fractal fumed silica nanoparticles and spherical silica nanoparticles with similar hydrodynamic sizes. The Emulsions stabilized by fumed silica were more stable than those stabilized by spherical silica. The improved stability was due to the closely packed multiple layers of fractal fumed silica nanoparticles at the O/W interfaces and a network structure formed between the emulsion droplets. These kinds of network and bridge structures were also reported in Pickering emulsions stabilized by cellulose nanorods or nanofibers, which always enhanced the viscosity of emulsions and restricted droplet coalescence. The morphology of nanoparticles affects their adsorption energy, their manners of packing at the O/W interface, and the interparticle interactions and viscosities of emulsions, all of which can give rise to varied behaviors and applications. Inorganic mesoporous nanoparticles have been widely applied in catalysis, energy storage, medicine, absorption, and separation due to their high specific surface areas, large pore volume, tunable morphologies, and higher reactivities of their functional groups on their inner pore surfaces. In our previous work, Pickering emulsions stabilized by spherical mesoporous silica nanoparticles and the pH-insensitive cationic surfactant cetyltrimethylammonium bromide (CTAB) showed novel responsiveness to the addition of bases and acids. The rich pore structure of MSNPs plays a critical role in their novel stimuli-response behavior. However, the effects of MSNP morphology are still unclear. In this study, therefore, mesoporous silica nanoparticles of different shapes (spherical, rod-like, thread-like) were synthesized and used as emulsion stabilizers, together with a conventional cationic surfactant, dodecyltrimethylammonium bromide (DTAB). The effects of the morphology of the mesoporous nanoparticle on the stability and stimuli-responsive properties of Pickering emulsions were then investigated. The results were expected to enrich the knowledge of Pickering emulsions stabilized by mesoporous nanoparticles and their application.

2. EXPERIMENTAL SECTION

2.1. Materials. Dodecyltrimethylammonium bromide (DTAB, ≥99.0%), was purchased from Aladdin Bio-Chem Technology Co. (Shanghai, China). Tetraethyl orthosilicate (TEOS, AR), cetyltrimethylammonium bromide (CTAB, ≥99.0%), aqueous ammonia (NH₃·H₂O, AR, 25–28%), ethanol (AR), n-octane (≥98.0%), hydrochloric acid (HCl, 36–38% in water), sodium hydroxide (NaOH, 99%), styrene (AR), and 2,2′-azobis(2-methylpropionitrile) (AIBN, 98%) were purchased from Sinopharm Chemical Reagent Co. (Shanghai, China). All materials were used as received. Aqueous solutions were prepared using ultrapure water (18.2 MΩ cm).

2.2. Method. Synthesis of MSNPs. MSNPs with various morphologies were synthesized using surfactant micelles as the soft template in basic conditions. A CTAB aqueous solution and a volume of aqueous ammonia were mixed and stirred at room temperature for 1 h. TEOS was added to the mixture at a rate of 5 mL·min⁻¹. The reaction was continued for 4 h with constant stirring. The morphologies of the MSNPs were controlled by varying the compositions of the reactants (CTAB, H₂O, NH₃·H₂O, and TEOS) and the stirring rate, as listed in Table 1. The resulting suspension was then incubated in a Teflon-lined autoclave at 100 °C for 24 h. The solid products were then separated, purified, and dried. MSNPs were obtained after removal of the soft template (CTAB) by calcining the solid at 550 °C for 5 h.

Characterization of MSNPs. The morphologies of the MSNPs were characterized by transmission electron microscopy (TEM) (JEOL JEM-2100, Tokyo, Japan) and scanning electron microscopy (SEM) (SU-8010 instrument, Hitachi, Tokyo, Japan). The mesoporous structures of the MSNPs were investigated by X-ray diffraction (XRD) (D8 Advance, Bruker, Karlsruhe, Germany) and N₂ adsorption–desorption isotherms (ASAP 2020 MP, Micromeritics, Norcross, GA, USA).

Preparation of Pickering Emulsions. MSNPs (0.021 g, 0.3 wt %) were dispersed in 7 mL DTAB aqueous solutions at various concentrations by sonication for 50 W for 1 min (FS-250N, Shanghai, China). A 7 mL volume of n-octane was then added. The mixtures were homogenized at 12,000 rpm for 2 min (T18 basic, S18N-10G head, IKA, Staufen im Breisgau, Germany) and afterward stored in an incubator at 25 °C. The concentrations of MSNPs and DTAB were calculated relative to the volume of the water phase. The volume ratio between the oil and water phases was 1:1.

Characterization of Pickering Emulsions. A drop of Pickering emulsion was added to the water and oil phases in order to test for the style of emulsion formed. If the droplets dispersed into the water quickly, the emulsion type was O/W; otherwise, it was water-in-oil (W/O). Photos of the Pickering emulsions were taken with a digital camera. The droplet images of the Pickering emulsions were obtained using an optical microscopy system (VIHX-100, Keyence Co., Itasca, IL, USA). The size distribution of droplets was determined by image analysis, for which 200 droplets were analyzed and measured for each sample. The number-average diameter (Dₙ), volume-average diameter (Dᵥ), and the polydispersity index (PDI) were calculated according to the following equations:

\[
D_n = \frac{\sum_{i=1}^{\infty} n_i D_i}{\sum_{i=1}^{\infty} n_i}
\]

\[
D_v = \frac{\sum_{i=1}^{\infty} n_i D_i^3}{\sum_{i=1}^{\infty} n_i D_i^3}
\]

\[
PDI = \frac{D_v}{D_n}
\]
Figure 1. SEM images of (A) spherical, (B) rod-like, and (C) thread-like MSNPs.

Figure 2. Digital photos of mixtures of n-octane and suspensions, containing 0.3 wt % MSNPs and DTAB at various concentrations (mmol·L⁻¹; labels in A), taken 6 months after they were homogenized. The MSNPs were (A) spherical, (B) rod-like, and (C) thread-like.

where \( n_i \) is the number of droplets with the diameter of \( D_i \).

**SEM Images of Droplets in Pickering Emulsions.** Styrene-in-water Pickering emulsions were prepared with identical volumes (7 mL) of a styrene−AIBN mixture (100:2, w/w) and aqueous dispersions containing 0.3 wt % MSNPs of various morphologies and 0.6 mmol·L⁻¹ DTAB. Following homogenization, the Pickering emulsions were polymerized at 40 °C for 24 h without stirring. The resulting polystyrene microspheres were washed, separated, and observed by SEM operated at 5.0 kV.

**Reversible Cycling of Switchable Pickering Emulsions.** A volume of concentrated NaOH solution \( (n_{NaOH} = n_{DTAB}) \) was added to the stable Pickering emulsions to observe the demulsification phenomenon. A volume of concentrated HCl solution \( (n_{HCl} = n_{NaOH}) \) was subsequently added to the NaOH-containing samples. The mixtures were homogenized once again to observe the re-emulsification phenomenon.

**Surface Tension Measurements.** DTAB solutions in combination with MSNPs of various morphologies were prepared in either the presence or absence of NaOH \( (n_{NaOH} = n_{DTAB}) \). All the solutions were aged for 24 h to attain equilibrium. The surface tension measurements were obtained using a DCAT-21 type tensiometer (DataPhysics, Santa Clara, CA, USA) with a Pt–Ir Du Noüy ring at 25 °C.

**3. RESULTS AND DISCUSSION**

**3.1. MSNPs with Various Morphologies.** MSNPs with different morphologies were synthesized in our lab according to the reported method. These MSNPs had large specific surface areas in the range of 896−1100 m²·g⁻¹, similar to the typical mesoporous silica particles previously reported. The morphology of the nanoparticles was controlled by the composition of reactants (CTAB, H₂O, NH₄OH, and TEOS) and the stirring rate. Figure 1 shows SEM images of the prepared spherical, rod-like, and thread-like MSNPs. The spherical MSNPs had an average diameter of approximately 150 nm (Figure 1A). The rod-like MSNPs had an average diameter of approximately 250 nm, and a length of approximately 1 μm (Figure 1B). The thread-like MSNPs had an average diameter of approximately 80 nm, and a length of approximately 5 μm (Figure 1C). The characteristics of MSNPs are listed in Table 1. These MSNPs had narrow pore size distributions and regular mesopore structures. The TEM, XRD, and N₂ adsorption–desorption isotherm data are available in the Supporting Information (Figures S1−S5).

**3.2. Pickering Emulsions Stabilized by MSNPs in Combination with DTAB.** The MSNPs (0.3 wt %) with various morphologies were dispersed in DTAB solutions of different concentrations, following which, an equal volume of n-octane was added to each. The mixtures were first homogenized and then stored in an incubator at 25 °C. Images of the resulting solutions are shown in Figure 2. As reported, bare silica nanoparticles were too hydrophilic to stabilize the emulsions and so were bare MSNPs (see Figure 2 at C_DTAB = 0 mmol·L⁻¹). In the presence of a cationic surfactant, these MSNPs can be hydrophobized in situ and act as effective emulsifiers to stabilize the emulsions. For spherical MSNP systems, as shown in Figure 2A, the Pickering emulsions were unstable at DTAB concentrations below 0.2 mmol·L⁻¹. Phase separations occurred within 2 days. For DTAB concentrations above 0.2 mmol·L⁻¹, stable Pickering emulsions lasting more than 6 months were obtained. Similar phenomena were observed for the Pickering emulsions stabilized by rod-like MSNPs and DTAB (Figure 2B). The synergistic behavior of thread-like MSNPs and cationic surfactants seems to be more effective for stabilizing the emulsions. Stable Pickering emulsions can be produced at lower DTAB concentrations of approximately 0.1 mmol·L⁻¹ (Figure 2C).

Figure 3 shows optical micrographs of the prepared Pickering emulsions. The average diameter of the droplets in these emulsions stabilized by spherical and rod-like MSNPs was 30 ± 5 μm at DTAB concentrations of 0.3−0.6 mmol·L⁻¹ (Figure 3A,B). The average diameters of droplets in Pickering emulsions stabilized by thread-like MSNPs were 43.4 μm at 0.4 mmol·L⁻¹ DTAB and 26.8 μm at 0.6 mmol·L⁻¹ DTAB (Figure 3C). Similar variations in droplet sizes with surfactant concentrations were also reported for conventional Pickering emulsions. With increasing DTAB concentrations, the droplet sizes of all Pickering emulsions became more uniform. In the reported nanosilica Pickering emulsions, the average diameters of droplets were typically between 10 and 100 μm.
The droplets in Pickering emulsions stabilized by thread-like MSNPs and 0.1–0.3 mmol·L⁻¹ DTAB were extremely large, however (Figures 3 and S6). The average diameter of these droplets was approximately 700 μm, which was about 20 times larger than those of conventional droplets. This was an intriguing phenomenon, considering that these large droplets were able to resist coalescence over a period of 6 months or even remain dispersed after heating in an oven at 50 °C for 48 h (Figure S7). The morphology of the thread-like MSNPs is likely to be responsible for this unique behavior. Huang et al. prepared O/W Pickering emulsions using two-dimensional (2D) graphite oxide (GO) sheets as stabilizers. The oil droplets thus obtained were also very large, ranging between 0.267 and 1.347 mm in diameter as the GO concentration varied from 0.95 down to 0.0095 mg·mL⁻¹. These abnormal phenomena indicated the tremendous effect of nanoparticle morphology on the microstructure and stability of Pickering emulsions. In our study, the thread-like MSNPs had a high AR (ratio of long to short axis), as did the GO (ratio of lateral size to thickness). When absorbed at the O/W interfaces, these nanoparticles had limited freedom due to restricted rotation. Their orientations were thus kinetically trapped at the interface, with the long axis parallel to the interface. The alignment of the nanoparticles in this way resulted in interfaces with low curvatures. Moreover, the long thread-like MSNPs might have been entangled with each other at the O/W interfaces and even in the continuous phase and thus formed a network-like structure, which reduced the coalescence of droplets and enhanced the stability of the emulsions. SEM is expected to provide direct evidence of the location and orientation of MSNPs at the O/W interfaces. However, the in situ observation of an emulsion droplet using SEM is impossible due to solvent evaporation under vacuum. To achieve this, Pickering emulsions stabilized by 0.6 mmol·L⁻¹ DTAB together with 0.3 wt % MSNPs were prepared using styrene as the oil phase instead of n-octane. Polymerization of styrene was induced in order to solidify the emulsion droplets for observation. The results are shown in Figure 4. All three MSNPs were located at the surfaces of the droplets. This indicated that although the MSNPs used had diameters of hundreds of nanometers to several micrometers, they did adsorb at the O/W interface and serve as stabilizers. The sizes of traditional nanosilica particles used in preparing Pickering emulsions have usually been in the range of 20–200 nm. Larger particles failed to remain at the interfaces due to the effect of gravity. However, MSNPs are characterized by their low bulk densities, which lead to a decreased gravity effect. In this study, the MSNPs used were much larger in size, which could be adsorbed at the interface.

The spherical MSNPs distributed at the surface of the oil droplets were similar to those formed in conventional Pickering emulsions. The rod-like and thread-like MSNPs located at the O/W interface were oriented with some of their long axes parallel to each other. The packing of nanoparticles at the interface was denser in the case of both spherical and rod-like MSNPs. However, the packing of thread-like MSNPs was loose, whereas the packing of either spherical or rod-like MSNPs was more densely organized. The surface coverage of MSNPs was affected by the ARs of nanoparticles, which could be adsorbed at the interface. Larger ARs of nanoparticles lead to a lower coverage of the O/W interface. Similar effects of ARs on the surface coverage and stability of Pickering emulsions were also observed in O/W Pickering emulsions stabilized by silica microrods with various ARs (Figure 4A,C,E). Obviously, the ARs of nanoparticles directly affect surface coverage. Capron et al. reported the surface architecture of Pickering emulsions stabilized by cellulosic nanorods with various ARs, in which short nanocrystals were densely organized, while longer nanocrystals had low coverage, with most of the nanocrystals involved in the network of the material. Similar effects of ARs on the surface coverage and stability of Pickering emulsions were also observed in O/W Pickering emulsions stabilized by silica microrods with various ARs from 1 to 16. In general, particles with a higher AR showed flexibility to some extent in a multiphase system, which is proportional to the AR. These particles could behave like flexible threads in the Pickering emulsions systems. This might also have been the situation in the current study. As shown in Figure 4E (indicated by arrows), some of the thread-like MSNPs were inserted vertically into the droplets and

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**Figure 3.** Optical micrographs of Pickering emulsions stabilized by 0.3 wt %: (A) spherical, (B) rod-like, and (C) thread-like MSNPs in situ with different concentrations of DTAB (mmol·L⁻¹) as indicated, with a bar scale of 50 μm if without a special mark.

**Figure 4.** SEM images of polymerized styrene-in-water emulsions stabilized by 0.6 mmol·L⁻¹ DTAB in combination with 0.3 wt % MSNPs of various morphologies: (A,B) spherical, (C,D) rod-like, and (E,F) thread-like.
resulted in the fuzzy edges of the solidified spheres. With this alignment, the thread-like MSNPs were possibly intertwined and formed a three-dimensional (3D) network. The detailed structure shown in the SEM image taken directly following drying of the emulsion containing thread-like MSNPs implied the formation of a 3D network structure (Figure S8).

3.3. Switchable Behaviors of Pickering Emulsions.

Irrespective of the morphology of the MSNPs, all of the prepared stable Pickering emulsions remained their original appearances for more than 6 months. Following addition of a certain quantity of NaOH ($n_{\text{NaOH}}:n_{\text{DTAB}} = 1:1$), rapid demulsification was observed in the Pickering emulsions stabilized by spherical and rod-like MSNPs in combination with DTAB (Figures 5 and S9) within 10 min. The emulsions were separated into two phases, with a clear oil phase on the top and a turbid water phase containing nanoparticles at the bottom. Following addition of HCl ($n_{\text{HCl}}:n_{\text{NaOH}} = 1:1$), stable Pickering emulsions were reformed following homogenization. The average droplet size of the reformed emulsions was 30 μm (Figures S10 and S11) within 10 min. The emulsions were separated into two phases, with a clear oil phase on the top and a turbid water phase containing nanoparticles at the bottom. Following addition of HCl ($n_{\text{HCl}}:n_{\text{NaOH}} = 1:1$), stable Pickering emulsions were reformed following homogenization. The average droplet size of the reformed emulsions was 30 μm (Figures S10 and S11), which was close to those of the original emulsions. By alternately adding HCl and NaOH, the Pickering emulsions could be switched between stable and unstable states. The emulsification/demulsification cycle could be repeated more than 60 times. Similar phenomena have also been reported previously, showing the novel behavior of mesoporous nanoparticles when preparing switchable Pickering emulsions. The concentrations of NaOH and HCl required to induce the demulsification/emulsification were very low (<1 mmol·L$^{-1}$), which have no effect on the morphology of the MSNPs (see SEM images in Figures S12–S14). Thus, the switchable behavior was attributed to the varied interactions between MSNPs and the surfactants. The inner channels and outer surfaces of the MSNPs contained numerous silica hydroxyl groups, which have high reactivity. In the presence of NaOH, silica hydroxyl groups were transformed into anionic forms, which strongly absorb DTAB molecules by means of electrostatic interactions. Compared with the outer surface, there were more silica hydroxyl groups in the inner surface of MSNPs. Due to the large specific surface areas of MSNPs, most of the DTAB molecules were adsorbed into the inner channels (see the schematic illustration in Figure 6). As a result, the MSNPs became hydrophilic and were thus unable to stabilize the emulsions. With further addition of HCl to neutralize the NaOH, the silica hydroxyl groups were regenerated. The DTAB molecules were released from the inner channels, and the MSNPs were hydrophobized again, enabling them to stabilize the emulsions.

In contrast, the Pickering emulsions stabilized by thread-like MSNPs and DTAB behaved totally differently. As shown in Figure 7, following addition of NaOH, the volume of the water phase at the bottom increased, but no obvious phase separation was observed. The microscopy images showed large droplets with submicrometer diameters in the emulsions, similar to those shown in Figure 3C. The Pickering emulsions in this state were stable even after heating at 50 °C for 48 h or after stirring for several hours or adding excess NaOH ($n_{\text{NaOH}}:n_{\text{DTAB}} = 10:1$). Following addition of equimolar quantities of HCl to the NaOH and homogenization, stable Pickering emulsions with small droplet sizes (~30 μm) were reformed. The transformation from small-sized droplets to large droplets could also be repeated for at least 10 times by alternately adding HCl and NaOH repeatedly.

The surface tension results for DTAB solutions in the presence of various MSNPs are shown in Figure 8. Following
addition of NaOH \( (n_{\text{NaOH}} = n_{\text{DTAB}}) \), the surface tensions of these solutions increased with values close to that of water (72 mN·m\(^{-1}\)), even at a relatively high DTAB concentration of 5 mmol·L\(^{-1}\). This showed that there were few free DTAB molecules in the solution. Most of the DTAB molecules were absorbed into the inner mesopores of the MSNPs. These results proved that, for both spherical and rod-like MSNPs, the interactions between nanoparticles were similar when adsorbed at the O/W interface. However, for thread-like MSNPs, they could be entangled at the interfaces with each other, forming a cross-link and 3D network structure and resulting in long-range interactions that affect the whole interfacial film. Therefore, after the MSNPs were converted from amphiphilic to hydrophilic, the strong cross-linking between the thread-like MSNPs restricted the further coalescence of droplets and made the dispersion of droplets with large size possible. In general, the morphology of nanoparticles had no effect on their in situ hydrophobilization process but affected the interactions between nanoparticles and their orientations and arrangements at the interfaces.

4. CONCLUSIONS
Irrespective of the morphology of the MSNPs (spherical, rod-like, or thread-like), stable oil-in-water (O/W) Pickering emulsions can be prepared using MSNPs in situ hydrophobized by a cationic surfactant DTAB as stabilizers. Although the sizes of the MSNPs were in the range of hundreds of nanometers to several micrometers, all three MSNPs were adsorbed at the O/W interface. The low bulk densities of the MSNPs led to a decreased gravity effect, which allowed them to remain at the interface. These Pickering emulsions were thus characterized by adsorption layers composed of MSNPs with high specific surface areas and multiple adsorption sites. They are especially useful for heterogeneous catalysis, organic synthesis, and controlled drug release. The properties of Pickering emulsions were also...
significantly affected by the morphologies of the nanoparticles. With increasing nanoparticle anisotropy, adsorption of nanoparticles with high anisotropies at the O/W interface was less dependent on their surface hydrophobicity. For thread-like MSNPs (aspect ratio (AR) ≈ 60), extremely large droplets with submicrometer diameters were observed at a suitable concentration of cationic surfactant. The orientations of these nanoparticles were kinetically trapped at the O/W interface, with their long axes oriented parallel to the interface, resulting in interfaces with low curvatures. Our results demonstrate that the microstructures and characteristics of Pickering emulsions can be modulated effectively by altering the morphology of the nanoparticles. The present system also provides a new approach for synthesis of functional materials using the Pickering emulsions as templates. Our study has, for the first time, revealed the relationship between the morphology of mesoporous nanoparticles and the characteristics of Pickering emulsions. These results enrich our knowledge of the formulation of Pickering emulsions and expand their application.

■ ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c03215.

The collected TEM, BET, and XRD data for the MSNPs, the optical micrographs of the Pickering emulsions, the SEM images of the dried Pickering emulsions, and the digital photographs of Pickering emulsions after several cycles (PDF)

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D.X. and Y.J. designed the experiment, wrote the original draft, and participated in the review and editing. K.L., X.Y., and Y.Z. contributed to the data collection, data analysis, and interpretation. D.X. was in charge of the project administration. All authors contributed to the final manuscript and have given approval to the final version of the manuscript.

Notes
The authors declare no competing financial interest.

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