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ARTICLE

Engineering hybrid microgel as particulate emulsifier for reversible Pickering emulsions

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Thermo-responsive microgels are unique stabilizers for stimuli-sensitive Pickering emulsions that can be switched between the state of emulsification and demulsification by changing temperature. However, directly temperature-triggering phase inversion of microgel-stabilized emulsion remains a great challenge. Here, a hybrid poly(N-isopropylacrylamide)-based microgel has now been successfully fabricated with tunable wettability from hydrophilicity to hydrophobicity in a controlled manner. The engineering microgels are synthesized from an inverse emulsion stabilized with hydrophobic silica nanoparticles, and the swelling-induced feature can make the resultant microgel behave like either hydrophilic or hydrophobic colloids. Remarkably, the phase inversion of such microgel-stabilized Pickering emulsions can be in-situ regulated by temperature change. Moreover, the engineering microgels were capable of stabilizing water-in-oil Pickering emulsions and encapsulation of enzyme for interfacial bio-catalysis, as well as rapid cargo release triggered by phase inversion.

Introduction

Microgels are soft and deformable colloid particles that can swell or shrink in a solvent with external stimulus. 1-4 Touted as intelligent materials, microgels have received great attention 5, 6 and have been employed as rheology modifiers, 7-8 delivery vehicles,9 emulsion stabilizers,10, 11 micropattern templates,12 microreactors,13 and actuators.14 Particularly, microgels are capable of spontaneously self-assembling onto the oil/water interface and rapidly lowering the interfacial energy.15-17 and Ngai et al. pioneered the use of poly(N-isopropylacrylamide-co- methacrylic acid) (PNIPAM-co-MAA) microgels for stabilization of pH and temperature responsive oil-in-water (o/w) Pickering emulsion in 2004.18 Since then, numerous studies have been reported on microgel-stabilized emulsions19 with a variety of responses, including CO2/N2, sugar addition,20 magnetic field,21 and oxidation.22

Typically, microgels are highly hydrophilic and preferentially stabilize o/w Pickering emulsions.23, 24 However, only forming o/w emulsions has application limitations, particularly in the preparation of aqueous-core microcapsules,25 interfacial bio-catalysis,26-28 gene delivery,29 and encapsulation of water-soluble actives.30 To address this issue, highly hydrophilic microgels were hydrophobized to some extent, allowing them to have an affinity for the oil phase and therefore stabilize water-in-oil (w/o) Pickering emulsions.31 In such case, phase inversion of microgel-stabilized emulsions from one type to another is conceivable, for example, inversion of o/w to w/o emulsion, which is becoming increasingly important in petroleum chemistry, drug delivery, and biphasic catalysis.33-36 Nevertheless, directly triggering the phase inversion of microgel-stabilized Pickering emulsions remains a great challenge, and the primary availability of switching exclusively between the state of emulsification and demulsification. For the purpose of reversion between o/w and w/o emulsions, it requires the microgels especially capable of being altered with sufficient hydrophobicity from the intrinsic hydrophilic state. Watanabe et al. synthesized hydrophobized microgel for the first time to achieve stabilization of w/o Pickering emulsions with non-polar oils.32, 37 By changing the composition of the hydrophobized microgel, both o/w and w/o Pickering emulsions can be generated. However, the reversion of emulsion type from o/w to w/o was typically accomplished by increasing the grafted hydrophobic sites over the surface of microgels, i.e., microgels hydrophobized in different levels were strategically selected. For in-situ reversing the emulsion type by sole microgel (without changing the composition of microgel), the wettability of the microgel should be flexibly adjustable as hydrophobic or hydrophilic when the environment changes. Alternatively, coating the microgel with hydrophobic particles is an effective approach by taking the advantage of expansibility of microgel. When the microgel swells or collapses, the density of the hydrophobic particles on the surface decreases or increases, thus allowing the wettability of the microgel to be facilely adjusted.

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Herein, we report a hybrid poly(N-isopropylacrylamide) (PNIPAM)-based microgel that was engineered for the fabrication of reversible Pickering emulsions. The surface of PNIPAM microgel is coated with hydrophobic particles through an inverse Pickering emulsion template method, and magnetic response is integrated by embedding Fe$_3$O$_4$ nanoparticles into microgel. As a result, the hybrid microgel stabilized Pickering emulsion is able to be in-situ switched between o/w and w/o type. Furthermore, we show that the hybrid microgel in hydrophobic state can make a breakthrough in microgel-stabilized w/o Pickering emulsion for interfacial bio-catalysis. Moreover, an effective microencapsulation and burst release of water-soluble active is realized via the phase inversion of microgel-stabilized Pickering emulsion simply by hand shaking.

Results and discussion

The schematic synthesis and morphology of resulting hybrid microgels are depicted in Figure 1. As illustrated in Figure 1a, a w/o Pickering emulsion stabilized by hydrophobic silica nanoparticles (NPs) was prepared first, and the monomer, initiator, and crosslinker were all added in advance in the internal aqueous phase. Following polymerization, a hydrophobized hybrid PNIPAM microgel is expected to be formed from the w/o Pickering emulsion. Nearly irreversible adsorption of colloidal particles in Pickering emulsification and crosslinking polymer networks will make the silica nanoparticles coated on the microgel surface. These microgels were then collected and dispersed in water. Because of the change in the polymer-water affinity, PNIPAM-based microgel swells in water below the volume phase transition temperature (VPTT = 32°C) and shrinks above it. Optical micrographs of the w/o Pickering emulsion template (Figure 1b and S1) show that emulsion droplets had an average diameter of 4.2 µm, and in contrast, the average diameter of resultant microgels dispersed in water increased to 7.5 µm, owing to water swelling (Figure S2). These hybrid microgels still retained sufficient softness and deformability, as a collapsed state could be observed after loss of water (Figure 1c and 1d). And the surface of the microgel was relatively rough because of the distribution of hydrophobic silica NPs (Figure 1e). Additionally, no free small NPs were observed, indicating that the subsequent Pickering emulsion was completely stabilized by hybrid microgels. It is worth noting that confocal laser scanning microscopy (CLSM) observation revealed that the hybrid microgel had a hollow structure, with the shell composed of PNIPAM (Figure 1f and 1g).

Contact angle measurements revealed that the hydrophobic silica NPs on the surface of the resulting hybrid microgel considerably enhanced its hydrophobicity. At room temperature, the contact angle of a water drop on air was almost 90°, as illustrated in Figure 2a. In comparison to the pure PNIPAM microgels synthesized by precipitation polymerization and the hydrophobic silica NPs, the dynamic contact angle of the hybrid microgel shows it had an intermediate wettability. Furthermore, when the hybrid microgel was applied, the dynamic interfacial tension between water and tert-butyl methyl ether (MtBE) was dramatically reduced (Figure 2b), but the hydrophobic silica NPs had no noticeable effect alone, indicating that the hybrid microgel was interface active. Indeed, as seen in the optical microscopy and CLSM images of the w/o Pickering emulsion prepared at the oil/water volume ratio of 1:1 (Figure 2c-f), the hybrid microgels with hollow structure closely stacked to form a dense layer at the w/o interface.

Using hydrophobic silica NPs alone can only create w/o Pickering emulsions (Figure S3), regardless of the volume ratio of oil/water; and correspondingly, the PNIPAM microgel cannot form w/o Pickering emulsions (Figure S4). However, the type of Pickering emulsions stabilized by the hybrid microgels could be switched facilely by adjusting the oil/water volume ratios. For example, the as-prepared Pickering emulsion was w/o type

Figure 2. (a) Contact angles of a water drop on the films of the hydrophobic silica NPs, PNIPAM microgels, and hybrid microgels. (b) Dynamic interfacial tension between water and MtBE without (●) or with the hybrid microgel (●), hydrophobic silica NPs (▲), c, d) Optical micrographs of the w/o Pickering emulsion stabilized by the hybrid microgels. (e, h) CLSM images of the hybrid microgels at the w/o interface observed from different focus.
The phase inversion diagram of hybrid microgel-stabilized Pickering emulsion with different water fractions at different temperature. (d) Schematic illustration of the influence of water fraction (φ) and temperature on the phase inversion of as-prepared Pickering emulsions.

(Figure 3a and Figure S5) when the water/oil volume ratio was 1:1 at 28 °C; but when the water/oil ratio was 1.5:1, it became o/w type (Figure 3b). More significantly, altering the temperature in situ can also control the state of the resulting Pickering emulsions, due to the temperature sensitivity of PNIPAM. As illustrated, when the water/oil ratio was 1:1, and the temperature was decreased from 28 °C to 18 °C, the type of the hybrid microgel stabilized was reversible from w/o to o/w (Figure 3a). Even though the water fraction was higher than oil (water:oil = 1:5:1), an o/w Pickering emulsion can be successfully converted to a w/o type by raising temperature (Figure 3b), and a higher temperature can further cause the emulsion system to become demulsified (Figure S6). The results of dynamic contact angles in Figure 3c proved that the hybrid microgel displayed switchable wettability between hydrophobicity and hydrophilicity, allowing for the in-situ regulated formation of w/o or o/w Pickering emulsions via temperature change. Since the total amount of hydrophobic silica NPs on the microgel surface remained constant, it is believed that as the ambient temperature rises, the volume shrinkage of the hybrid microgel leads to denser surface coverage of the hydrophobic sites and thus the hybrid microgel would become more hydrophobic (Figure 3c). Therefore, the volume fraction of water (φ) at the point of phase inversion of the Pickering emulsions stabilized by hybrid microgels can be regulated by temperature change. As summarized in Figure 3d, Pickering emulsions with varying oil/water volume ratios were prepared for investigating the temperature-controlled type reversion of emulsions. When the temperature rose, the φ of emulsion reversion from o/w to w/o type was correspondingly increased. In comparison to adjusting the oil/water volume ratio, tuning temperature in situ to switch the type of the Pickering emulsion is obviously easier and more accessible. Overall, both the water/oil volume ratio and temperature can be utilized to control over the state of the

Notably, the hybrid microgel in hydrophobic state had sufficient hydrophobicity to stabilize the w/o Pickering emulsions with a variety of non-polar oils, such as toluene, cyclohexane, and isoctane (Figure S7). It highlights the great potential for encapsulation of enzymes within the interior aqueous phase, paving the way for applications in interfacial biocatalysis. The catalytic performance of lipase-loaded Pickering emulsion was initially examined by the esterification of 1-hexanol and hexanoic acid with toluene as the oil phase. In detail, lipase was dissolved and encapsulated in the internal aqueous droplet, while substrates and product were dissolved in the oil phase, with the catalytic reaction taking place at the w/o interface, as illustrated in Figure 4a. As a control, a biphasic system containing free lipase was employed. The conversion of esterification reaction reached more than 90% in four cases employing encapsulated lipases within one hour, but less than 34% for the biphasic group (Figure 4b). Furthermore, the catalytic performance in Pickering emulsions improved with the increase of the concentration of hybrid microgels, while the enzyme concentration remained constant. Figure S8 also shows that when the concentration of hybrid microgels increased, the average diameter of resultant emulsion droplets decreased. As a result, we reasoned that the higher conversion in the Pickering emulsions was due to the greatly enlarged water-oil interfacial area stabilized by hybrid microgels, which significantly improved the mass transfer of substrates and the accessibility of enzyme. Given the high cost of biocatalyst, the reusability is an important attribute, and magnetic separation is regarded as a convenient and effective method of recycling catalysts. It is worth noting that magnetic NPs can be easily incorporated into the hybrid microgels during the polymerization process, giving the hybrid microgel-stabilized Pickering emulsions, allowing for fabrication and adjustment of emulsion systems that meet production needs in a variety of situations, as depicted in Figure 3e.
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Figure 5. (a) Schematic representation of active release induced by phase inversion. (b) The w/o Pickering emulsion stabilized by hydrophobic silica NPs as a control group for active release. Red color in CLSM images indicates Nile red-staining oil phase.

This particulate stabilizer with magnetic responsiveness. As shown in Figure 4 c-d, the aqueous droplets carrying enzyme dispersed in oil can be promptly isolated using a magnet, and then the oil phase containing product can be readily removed and supplied to initiate the next cycle. Even after 10 cycles of consecutive use, the magnetic-responsive Pickering emulsion exhibited exceptional stability, as well the catalytic activity of enzyme had no discernible loss.

Controlled release is a perpetual hot topic in chemistry industry and biomedical applications. Herein, attributing from the reversible feature, the as-prepared w/o Pickering emulsion can be employed to protect water-soluble compounds, and then be released by phase inversion. As illustrated in Figure 5a, methylene blue, as a model substance, was primarily encapsulated in a w/o Pickering emulsion stabilized by hybrid microgel. When the w/o Pickering emulsion was transferred to water, it first floated on top of the water layer that was colorless and transparent. After hand shaking, the w/o Pickering emulsion was instantly converted to an o/w Pickering emulsion, resulting in rapid release of methylene blue. As a result, the bulk water became blue immediately. Furthermore, the oil droplets can be magnetically collected to realize the separation with bulk water. As shown in Figure 5b, the w/o Pickering emulsion stabilized by hydrophobic silica NPs was used as a control group, and the w/o emulsion was also suspended on the water, but phase inversion did not occur after shaking and methylene blue could not be released into the water layer.

Conclusions

In conclusion, we developed a simple approach for hydrophobizing PNIPAM-based microgels and employed them to construct reversible Pickering emulsions. The engineering microgel was composed of a dense PNIPAM shell and a rough surface incorporated with hydrophobic silica NPs, which allowed for swelling-induced changes in the surface wettability. Thus, the phase inversion ratio of oil to water in such microgel-stabilized Pickering emulsions can be simply controlled by temperature. We demonstrated that the hydrophobized microgels were capable of stabilizing w/o emulsions and encapsulating enzyme for interfacial bio-catalysis, and cascade catalysis is conceived by encapsulation another enzyme in the cavity of the hollow microgel. More importantly, the reversible feature can be exploited to protect hydrophilic actives in the w/o emulsion and to trigger release via emulsion phase inversion. Surprisingly, magnetic NPs were effectively integrated as functional sites in the engineering microgel for rapid collection, and further capabilities are envisioned in the future.

Author Contributions

H. Jiang: conceptualization, investigation, methodology, supervision, and writing - review & editing; S. Zhang: data curation, investigation, resources, and writing - original draft; G. Sun, X. Guan, and C. Yang: writing - review & editing; Y. Li: conceptualization, project administration, writing - review & editing, and supervision; T. Ngai: writing - review & editing, supervision, and funding acquisition.

Conflicts of interest

There are no conflicts to declare.

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