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Dynamic Interface Engineering to Drive Emulsion Catalysis: Progress and Challenges from Molecular Design to Industrial Applications

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ABSTRACT
Emulsion catalysis, as an emerging green catalytic strategy, realizes the intelligent regulation of interfacial properties through dynamic interfacial engineering, which can significantly enhance the reaction efficiency and reaction controllability. This paper reviews the design of surfactants and functionalized solid particles responsive to various stimuli (e.g., light, temperature, pH, magnetic field, etc.), describes the functions of interfacial domain-limiting effect and external field modulation in enhancing mass transfer and reaction selectivity, and briefly introduces its applications in organic synthesis, biocatalysis and continuous flow reactions. At the same time, the paper concludes that the technology still faces the challenges of cost, stability and scale-up in the actual production scale, and calls for interdisciplinary cooperation and policy support to promote its success from the laboratory to industrial applications.

KEYWORDS
Dynamic interfaces; Emulsion catalysis; Smart response; Pickering emulsion; Industrial applications

1 Introduction

Organic synthesis is an important part of the modern chemical industry, and its greening and high-efficiency transformation is of great significance in realizing the national "double-carbon" strategic goal. Catalytic technology plays a central role in this transformation, but the traditional multiphase catalytic system has bottlenecks such as low mass transfer efficiency and difficult catalyst recovery[1-2].

Emulsion catalysis cleverly enriches catalysts at the huge oil-water interface, combining the high efficiency of homogeneous catalysis with the ease of separation of multiphase catalysis [3-4]. However, the static nature of the interface and operational instability constrain its further development.

The proposal of dynamic interface engineering provides new ideas to solve the above problems [5-7]. Through the design of intelligent response materials, the emulsion system can respond to external stimuli such as light, temperature, pH, magnetic field, etc., so as to regulate the interface state in real time, realizing the reaction process with high efficiency and controllability [8-9].

In this paper, we will review the research progress of dynamic interfacial engineering-driven emulsion catalysis and look forward to its future development from four aspects: molecular design, interfacial engineering mechanism, application practice and industrialization challenges.

2 Revolutionizing molecular design: building intelligent responsive interfaces

The interface is the center stage of emulsion catalysis, and its performance is directly determined by the molecules that construct it. The successful application of dynamic interface engineering lies in the ability of the interface to sense and respond to external stimuli through sophisticated molecular design, thus realizing the precise regulation of the catalytic process [8, 10].

2.1 Smart response surfactants

While conventional surfactants constitute static interfaces, smart-responsive surfactants can actively regulate interfaces by undergoing reversible property changes in response to external stimuli.

PH-responsive system: A new pH-responsive Gemini surfactant (Figure 1), GTL, developed by Prof. Wang Guojie's team at the University of Science and Technology Beijing (USTB), exhibits a standardized baryonic configuration under alkaline conditions (pH $\geqslant$ 8.0).

The interfacial tension decreased to about 3 mN-m-^{1}; under acidic conditions (pH $\leqslant$ 6.0) it was transformed to a single-chain conformation, and the interfacial tension increased to about 27 mN-m-^{1}, realizing a reversible emulsification and demulsification cycle [8].

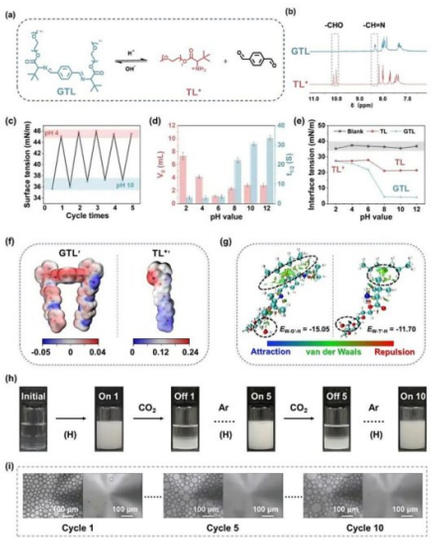

Figure 1 PH response behavior of Gemini surfactants and reversible gas response of emulsions [8]

Light Response System: (Figure 2) Arakawa's team at Tokyo University of Science has reported that the neutral nitrobenzospiro-pyran derivative HSP, which can be isomerized to the cationic state HMCH under UV light and acidic conditions, drastically reduces the toluene/water interfacial tension from 30 mN/m to 17 mN/m in 10 seconds, which is far more than that of conventional azobenzene analogs (Δγ is usually <5 mN/m), and realizes the photocontrol of the stability of emulsion "switch" [11].

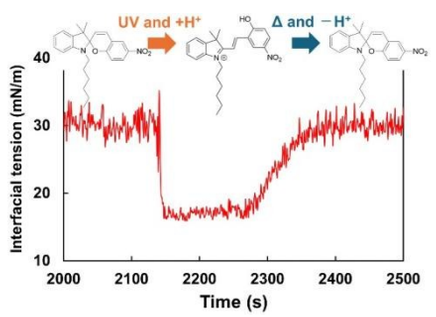

Figure 2 Mechanisms of photoisomerization and protonation to change the molecular structure and charge of HSP and surface tension magnitude versus time curves [11]

Redox response system: Jiang Jianzhong-Cui Zhenggang team of Jiangnan University designed a surfactant containing ferrocene groups with a structure that can be reversibly transformed between single-head-single-tail type and double-head-single-tail type[12]. (Figure 3) The interfacial potential of oil droplets was significantly enhanced after oxidation, and the emulsion could be stabilized at a very low concentration with the synergistic effect of trace alumina nanoparticles, and the reversible transformation of emulsion type could be achieved.

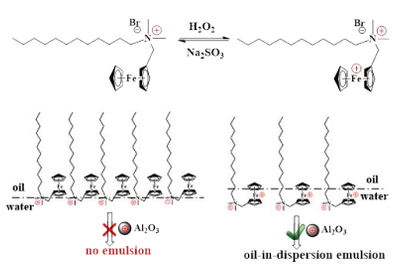

Figure 3 Schematic representation of the structural formula of surfactant FcN+C12 and its redox stimulus response [12]

CO_2 response system: Amidine-based surfactants for CO2/N2 emulsification/breaking were first reported by Jessop et al [13]. Using CO_2 as a green stimulant, amidinamides such as long-chain alkyl-modified amidines can achieve a reversible transition between nonionic and ionic forms when CO_2 is passed in/out, thus controlling the emulsification and emulsion-breaking, and the process does not require any heating or addition of chemicals.

Temperature-sensitive and magnetically-responsive systems: The temperature-sensitive polymer PNIPAM can utilize its LCST properties to achieve thermally-controlled demulsification [14]. The magnetically responsive system, on the other

hand, allows for convenient recovery of the catalyst by introducing magnetic components such as Fe_3O_4.Jangwoo et al. prepared magnetic colloidal surfactant catalysts by patching catalytic nanoparticles (Ag, Pd) and Fe2O3 nanoparticles onto the surface of amphiphilic Janus particles (JMPs) [15]. (Figure 4) The catalytic nanoparticles were co-modified on the surface of Janus particles with Fe_3O_4 nanoparticles, and the prepared catalysts retained high activity after multiple cycles, the prepared catalysts still maintain high activity and can be easily separated by magnetic field.

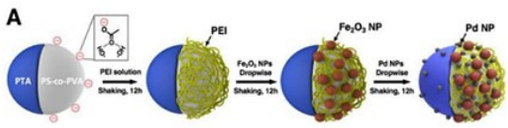

Figure 4 Schematic representation of the synthesis of patchy JMPs from NPs and iron trioxide NPs [15]

2.2 Functionalized solid stabilizers--Pickering emulsifiers

Pickering emulsions use solid particles as emulsifiers and offer the advantages of high stability, low toxicity and ease of functionalization. Janus particles + Pickering emulsion: Yang Hengquan's team at Shanxi University designed dumbbell-shaped two-component mesoporous Janus silica nanoparticles (Figure 5), whose hydrophilic-hydrophobic anisotropy enables them to exist stably at the oil-water interface, and whose vertical mesoporous pores can simultaneously and efficiently transport both oil-soluble and water-soluble reactants to the interfacial catalytic center [16]. In the hydrogenation reaction of chlorinated nitrobenzene, near 100% conversion and up to 99.6% selectivity were achieved.

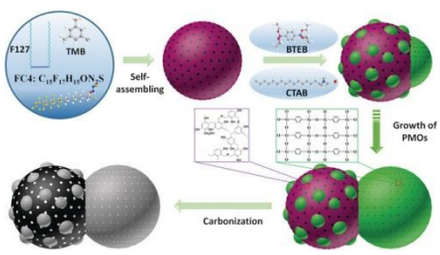

Figure 5 Anisotropic dumbbell-like two-component mesoporous carbon-organosilicon Janus particles with asymmetric wettability were successfully synthesized by combining mesoporous organosilicon spheres with mesoporous resorcinol-formaldehyde spheres [16]

Magnetic composite particles + Pickering emulsion: The Fe_3O_4@PDA@Si composite magnetic particles synthesized by Xiaohuo Huang's team at Zhejiang Ocean University have the conditions for stabilizing Pickering emulsions and good magnetic responsiveness (magnetic saturation strength up to 42.38 emu/g), which can realize rapid magnetic separation of emulsions to break the emulsion, and remain stable in high-temperature and high-salt environments, and the team's related technology has formed a The related technology of this team has formed a patent of invention (Patent No.: ZL201910625662.0)[17].

Bio-based particles + Pickering emulsion: In order to meet the sustainable development, the development of emulsifiers using natural materials such as cellulose nanocrystals, chitosan, humic acid, etc. has become a new trend. HAN et al. (2025) showed that humic acid, as a natural surfactant, can both promote pollutant desorption and transport and act as a soil conditioner to enhance microbial activity in the remediation of petroleum hydrocarbon contaminated soil [18].

3 Mechanisms of Interface Engineering--Revealing the Mysteries of Domain Restriction and Regulation

While molecular design gives interface a "dynamic" potential, interface engineering strives to deeply understand and maximize the "domain-limiting effects" and "regulatory capabilities" of dynamic interfaces to break through the limitations of traditional catalytic models. to break through the limitations of traditional catalytic modes.

3.1 Creating nano-reactors using interfacial domain-limiting effects

The liquid-liquid interface is a nanoscale microenvironment with specific thickness and properties, and its domain-limiting effects can significantly enhance the catalytic efficiency. The domain-limiting effects used to enhance the catalytic efficiency are as follows: Reactant Enrichment and Directed Alignment: Interfaces can spontaneously enrich amphiphilic reactants and catalysts, resulting in localized concentrations at the interface that are much higher than in the bulk phase. The team of Carlos Baiz and Hang Ren at the University of Texas found that adsorbed DMSO can change the size of interfacial water clusters and hydrogen-bonding network in platinum-surface hydrogen-extraction reactions (HERs) through the nano-restricted-domain effect, thus significantly affecting HER kinetics (Figure 6) [19].

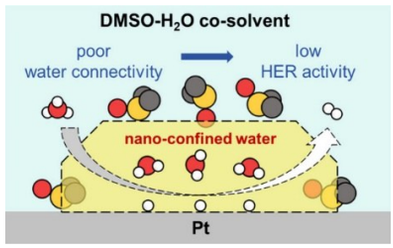

Figure 6 Modification of HER kinetics by adsorption of DMSO by nano-restricted domain water clusters in DMSO-H2O co-solvents [19]

Interface effects dominate: The team of Associate Professor Fu-Jie Tang at Xiamen University and the Max Planck Society in Germany have found through a collaborative study that when water is confined to a nano-space larger than 8 Å, its structural properties are mainly determined by interfacial chemistry rather than geometrically confined domains [20]. This suggests that the reaction microenvironment can be optimized by regulating interfacial hydrophilicity and charge distribution. Construction of "nano-response cages": Solid particles can form dense structures at the Pickering emulsion interface, confining catalytic active sites, reactants and intermediates to a very small space, greatly enhancing mass transfer efficiency and inhibiting side reactions. Khan et al. (2024) achieved precise control of individual droplets and collective behavior by embedding magnetic nanoclusters, i.e., aggregates of FePt nanoparticles, inside oil droplets and modulating the orientation of the external magnetic field to reconfigure the Marangoni flow inside the droplets (Figure 7) [21].

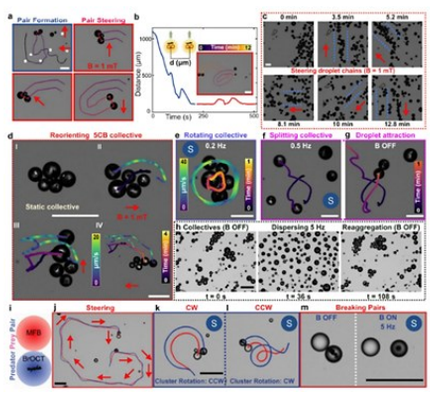

Figure 7 Control of the collective behavior of various emulsification systems, synergistic with droplet interactions [21]

3.2 Dynamic outfield precision control for intelligent manoeuvring

In addition to making the material interface-responsive in nature, it is also possible to realize the dynamic regulation of the interface directly through the action of external fields, which is a finer and more efficient means of hierarchical regulation. Electric field modulation: Although the direct application to emulsion catalysis is less studied, modulation of interfacial zeta potential by applied electric field, thus affecting reactant adsorption and transport, is a potential way to realize precise control of reaction rate in the future. Studies related to electric field manipulation of emulsion breaking by Wang et al. (2025) demonstrated the ability of electric fields to precisely control interfaces [22].

Magnetic field regulation: Magnetic fields are not only used to recover catalysts, but also to modulate interfacial structure and droplet behavior. Liu et al. (2019) found that reconfigurable droplets with ferromagnetism can be formed by controlling the self-assembly of magnetic nanoparticles at the interface to realize complex motions such as rotation and deformation, which provides a new way to build programmable microreactors (Figure 8) [23].

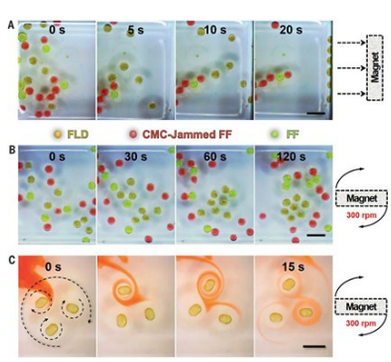

Figure 8 Classification of ferromagnetic liquid drops using static and rotating magnetic fields [23]

4 Application practice: from proof-of-concept to process development, from concrete experiments to industrial scale-up

Dynamic interface engineering-driven emulsion catalysis has demonstrated excellent performance in a wide range of important organic transformations and is expanding from batch flask reactions in the laboratory to a larger scale process, the continuous flow process.

4.1 Highly efficient organic synthesis reactions

The core strength of emulsion catalysis lies in the unique reaction microenvironment established through interfacial engineering, which allows it to excel in a wide range of organic reactions and to lay the foundation for continuous flow processes.

Asymmetric catalysis: A team of academician Li Can from Dalian Institute of Chemical Physics, Chinese Academy of Sciences, designed a surface-active chiral catalyst and applied it to catalyze the asymmetric Aldol reaction in chiral emulsion, which placed the reaction at a chiral interface and significantly improved the reaction activity and enantioselectivity (ee value >90%, up to more than 99%) [24].

Biodiesel Synthesis: Palm et al. (2025) utilized electrohydraulic discharges to generate a cavitation effect for simultaneous emulsification and transesterification reactions of methanol-oil systems [25]. Under room temperature and 1% CH_3NaO catalyst conditions, the methyl ester yield was as high as 97.9% in 15 min of reaction, which reduced the reaction time by 85% and energy consumption by about 40% compared with the conventional process.

Biocatalysis: Yang et al. (2022) developed a continuous flow biocatalytic system that confines enzymes and cofactors together inside Pickering emulsion droplets, realizing the cyclic regeneration of cofactors within the microenvironment [26]. In chiral alcohol synthesis, the conversion was over 90%, the ee value was greater than 99%, the catalytic efficiency was 2.7 times higher than that of the conventional two-phase reaction, and it was able to run continuously and stably for more than 350 hours (Figure 9).

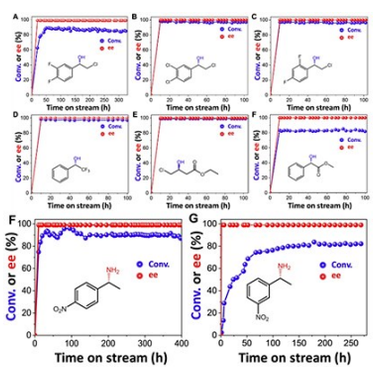

Figure 9 Conv. or ee values (%) for enzymatic reduction of various ketone and chiral amine compounds in a continuous flow system based on Pickering emulsions [26]

4.2 Reactor engineering and process innovation

Microreactor technology: In the study of Zhao et al. (2023), Pickering emulsion was applied to a microchannel reactor for multiphase catalytic oxidation reaction [27]. With the help of Pickering emulsion, the problems of catalyst adhesion and channel blockage caused by the solid catalyst particles coming into direct contact with the wall during the flow of the microchannel were effectively avoided. Under the Taylor flow, the system showed good stability and achieved high conversion and selectivity in the benzyl alcohol oxidation reaction. Continuous flow process: Yang et al. (2024) made a series of important contributions in this area by proposing the concept of Pickering emulsion droplet fixed-bed continuous flow catalysis [28]. By filling the emulsion in the fixed bed, the water-soluble catalyst is confined inside the emulsion droplets and the oil phase is free-flowing, which realizes the spatial isolation and proximity synergy of incompatible catalysts, and provides a new solution for multistep catalytic reactions (Figure 10).

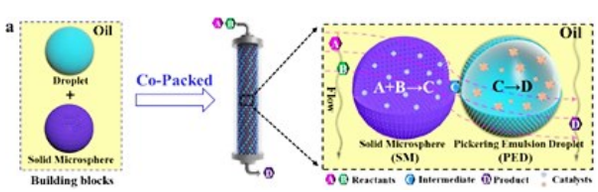

Figure 10 Graphical representation of the co-filling of PEDs (Pickering emulsion droplets) and SMs (solid mi-crospheres) in a bed reactor and the coexistence of PEDs with SMs [28]

5 Industrialisation challenges and interdisciplinary collaborative innovation

Upon analysis, despite the promising prospects of dynamic interface engineering-driven emulsion catalysis technology, it still faces serious challenges to truly realize large-scale industrial applications, which must be cracked through the approach of interdisciplinary collaborative innovation.

5.1 Current core bottlenecks to industrialization

Despite the promising future, the industrialization of this technology still faces serious challenges:

(1) Material cost and scale-up challenges: Many high-performance smart materials have complex synthesis pathways, making it difficult to meet the capacity and cost requirements for industrialization [29-30] .

(2) Insufficient stability over long periods of operation: catalyst deactivation (e.g., poisoning, agglomeration, wear) is a major obstacle in scale-up tests, with activity decaying up to 30% or more after long periods of operation [29-30].

(3) Process scaling and system integration is difficult: From laboratory flasks to industrial reactors, how to maintain emulsion stability, inhibit droplet aggregation, and achieve effective coupling of reaction-separation units are complex engineering problems [2] .

5.2 Towards industrialization: building a four-dimensional synergistic system of "chemistry-materials-engineering-policy"

A breakthrough in a single discipline cannot solve this kind of systemic problem, and an interdisciplinary synergistic innovation approach must be adopted in order to crack it step by step.

Chemistry-materials synergy: Shift from "performance-first" to "manufacturability-first", and develop synthesis pathways (e.g., continuous-flow synthesis of Janus particles) that can be easily scaled up at low cost.

Material-engineering synergies: Optimization of materials design based on industrial reactor conditions, e. g., development of clog-resistant ultrasonic microreactor technology to enhance mixing and mass transfer and solve clogging problems [31].

Engineering-policy synergy: Quantify the carbon emission reduction benefits based on full life cycle evaluation and techno-economic analysis, and provide the basis for the formulation of carbon tax, green subsidies and other policies [32].

Policy-chemical synergies: timely inclusion of proven green technologies in promotion catalogs, and incentives for enterprise adoption and R&D through policies such as tax breaks and special loans [33].

6 Conclusions

Dynamic interface engineering breaks the previous understanding of static interfaces by being perceptible, responsive and tunable, and subverts the traditional approach of emulsion catalysis, which fully realizes the combination of the advantages of high efficiency of homogeneous catalysis, the ease of separation of multiphase catalysis and the high selectivity of bionic catalysis, and it has a strong supportive role in the development of the next generation of green, high-efficiency and intelligent chemical synthesis technology. At present, the research in this field has gradually shifted from mainly basic mechanism research to how to do well in the research and development of application technology, and in the future, it is necessary to rely on the cross-fertilization between multiple disciplines to further advance the related work. Even though there are still some difficulties in materials, stability and engineering scaling-up, we have adopted an integrated innovation community of "industry-academia-research-politics" to realize the innovation of the whole process chain from molecular design to policy making, and upgraded the idea and technology of emulsion catalysis driven by dynamic interface engineering from laboratory results to industrial With dynamic interface engineering-driven emulsion catalysis technology, it is expected to play a very important role in China's green chemistry and "dual-carbon" strategy, and then become one of the core technologies in the chemical industry.

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