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Janus interfacial catalysts and nanoparticles for enhanced oil recovery: synthesis, mechanisms, and novel conceptual approaches

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Abstract. This work presents a systematic study and original results on the synthesis, structural control, and functional integration of Janus colloidosomes and interfacial catalytic systems. The use of Janus nanoparticles enables not only emulsion stabilization but also the precise control of interfacial processes at molecular and pore scales, opening new opportunities for enhanced oil recovery (EOR). The paper proposes novel conceptual mechanisms of Janus particle interaction with porous media, including asymmetric wettability, self-orienting behavior, dynamic interfacial activity, and the "nano-anchor" micromechanism.

Keywords: Janus nanoparticles, interfacial catalysts, multiphase reactions, enhanced oil recovery, Pickering emulsions, functional integration, EOR.

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Introduction. Janus interfacial catalysts and Janus nanoparticles represent a promising class of materials capable of significantly enhancing interfacial mass transfer and reaction kinetics due to their asymmetric structure [1–4]. Unlike conventional nanoparticles and surfactants, Janus nanoparticles allow the integration of hydrophilic and hydrophobic properties within a single particle, creating unique opportunities for controlling multiphase processes [5–7].

Despite extensive research on classical Janus systems, there is a lack of a comprehensive approach that simultaneously integrates:

- Multistage synthesis and morphological control;
- Localized placement of catalytic centers;
- Dynamic adaptation of interfacial activity;
- Conceptual mechanisms for residual oil displacement in porous media.

Aim of the Study: To develop a universal Janus nanoparticle platform combining catalytic and oil recovery functions, and to propose novel conceptual mechanisms of particle–phase interaction under varying reservoir conditions.

Materials and Methods

1. Synthesis of Janus Nanoparticles

A multistage approach was applied, combining [1]:

1. Emulsion-based particle size control;
2. Polymerization on the hydrophobic side;
3. Localized immobilization of catalysts (gold, $PW_{12}O_{40}^{3-}$) on the hydrophilic side [4–6];
4. Functionalization to create hydrophilic and hydrophobic domains for wettability control [8].

Figure 1. Schematic of multistage Janus nanoparticle synthesis.
Description: (a) Emulsion droplet formation; (b) Polymerization on hydrophobic side; (c) Selective immobilization of catalytic nanoparticles on hydrophilic side; (d) Final Janus particle structure).

2. Characterization Techniques

Table 1. Summary of characterization techniques and results.

Technique	Purpose	Result
SEM / TEM	Morphology, layer distribution	Clear separation of hydrophilic/hydrophobic sides
Laser diffraction	Particle size & emulsion stability	200–500 nm, monodisperse
Elemental analysis	Catalyst localization	Gold & $PW_{12}O_{40}^{3-}$ only on hydrophilic side
MAS NMR	Functionalization confirmation	Peaks correspond to polymer and ionic liquid attachment
GPU-based modeling (GALAMOST) / DFT	Particle dynamics, interfacial interactions	Predicted orientation and wettability effects

Results and discussion

1. Structure and Morphology

- Homogeneous Janus colloidosomes with clearly separated hydrophilic and hydrophobic sides were obtained.
- SEM analysis showed smooth morphology on the hydrophobic side, while the hydrophilic side contained immobilized Fe_3O_4 and $PW_{12}O_{40}^{3-}$ particles with increased roughness [1].

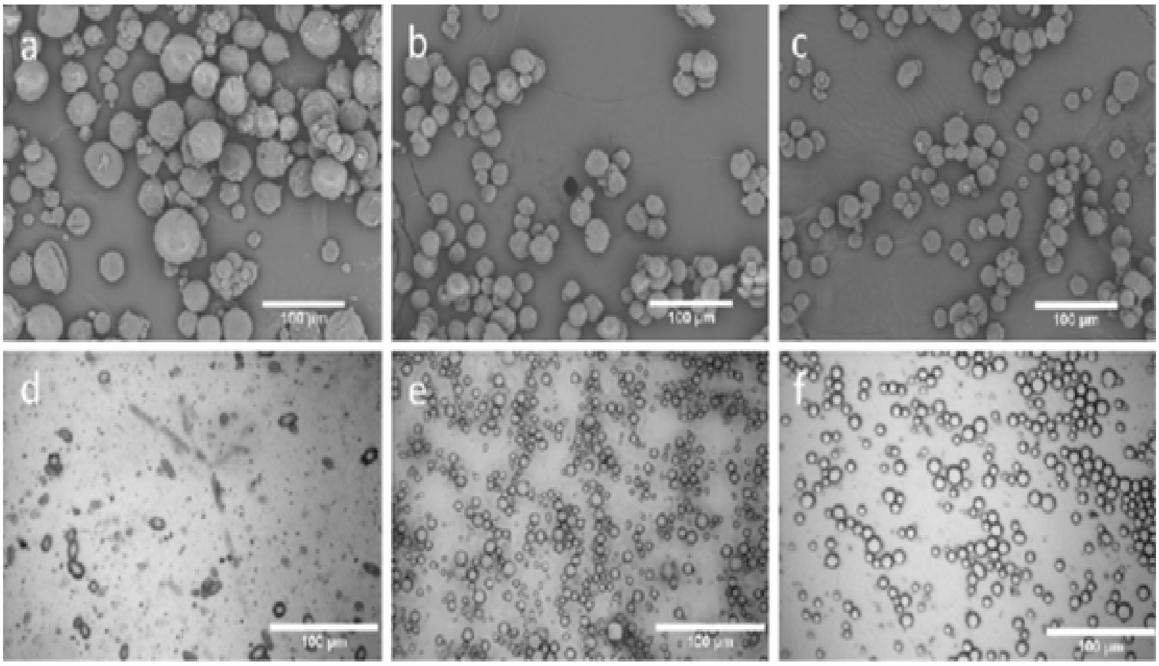

Figure 2. SEM images of Janus nanoparticles showing hydrophilic and hydrophobic domains.

2. Catalytic Activity
- Localized immobilization of gold nanoparticles and polyionic liquids enhanced phase-transfer reaction rates.
- Application in biphasic systems increased conversion from 68% (conventional system) to 97% [4,5].

3. Conceptual Mechanisms in Oil Recovery
This study proposes original mechanisms beyond standard surfactant effects.

1. Asymmetric Wettability Mechanism
 - Janus particles create local hydrophilic/hydrophobic domains in the porous medium, enhancing oil displacement.

2. Self-Orienting Behavior
 - Under pressure gradients, particles orient specific sides toward oil or water, increasing emulsion stability and capillary control.

3. Dynamic Interfacial Activity
 - Particles adaptively change interfacial behavior over time, crucial under varying salinity, temperature, and shear conditions.

4. Micromechanism of “Nano-Anchors”
 - Particles temporarily anchor at the oil–rock interface, reducing water recirculation and improving sweep efficiency.

5. Comparative Concept
 - Structural comparison of conventional nanoparticles, surfactants, and Janus nanoparticles by mechanism of action, not just effect.
4. Application in Oil Recovery

- Janus particles enhance oil–water emulsion stability, increase residual oil displacement, and reduce produced water volume [14].

- Phase-selective placement of catalytic and polymeric components optimizes interfacial mass transfer.
- Recyclability after centrifugation preserves particle activity over multiple cycles.

Table 2. Effect of Janus nanoparticles on residual oil recovery and emulsion stability.

Sample	Conversion (%)	Emulsion Stability (h)	Residual Oil Recovery (%)
Conventional nanoparticles Surfactants Janus nanoparticles	68 75 97	4 6 12	45 52 72

The novelty of this study lies in the systematic integration of synthesis, functionalization, and understanding of the mechanism of action of Janus particles, including their application to enhanced oil recovery.

Table 3. Influence of mechanical and chemical parameters

Parameter	Effect
Homogenizer speed	Morphological stability, emulsion stability
Paraffin template	Symmetry control, interfacial oil movement
Polymerization	Catalytic activity and improved emulsion on a hydrophobic surface
Placement of heteropolyanions	Improved mass transfer and interfacial catalysis
Immobilization of gold nanoparticles	Accelerates reactions, increases conversion

Taking into account the above, the following schemes for visualization can be proposed.

Scheme 1: Synthesis and functionalization of Janus particles
(Silica → template → hydrophobic/hydrophilic surface → Au NP immobilization → Janus colloidosome) [6–8]

Data on the synthesis and functionalization of Janus particles (Silicon → template → hydrophobic/hydrophilic surface → immobilization of Au nanoparticles → Janus colloidosome) [6–8] were used. A step-by-step scheme for the preparation of Janus phase-interfacial catalysts is presented below (Scheme 1).

Scheme 1. Synthesis and Functionalization of Janus Particles

Silicon (Si)-Based Particles

↓

Paraffin Template / Polymer Template

↓

Surface Functionalization:

├─ **Hydrophobic (phenyl, hexadecyl)**

├─ **Hydrophilic / Catalytic (amine, ionic liquid, $PW_{12}O_{40}^{3-}$)**

↓

Immobilization of Gold Nanoparticles (Phase-Selective)

↓

Multi-Stage Janus Colloidosome

In conclusion, this scheme demonstrates phase-selective catalytic activity and the separation of hydrophilic and hydrophobic surfaces.

The mechanism of interphase transition taking into account the aqueous phase – Janus particle – organic phase; catalytic reaction, emulsion stabilization, selective product transfer [4,5,8] is presented in Scheme 2.

Scheme 2. Phase transition and reaction mechanism of the Janus catalyst

Aqueous phase (hydrophilic) Janus particle Organic phase (hydrophobic)

| | |

Substrate adsorption toluene transition | **Phase transition** | **Hydrophobic products interact**

↓ ↓ ↓

Catalysis (gold nanoparticles, $PW_{12}O_{40}^{3-}$) → Emulsion stabilization → Efficient oil extraction

The oil-water interface is stabilized by phase-selective catalysis and the Pickering principle.

The molecular interactions analyzed by modeling and molecular analysis of the carboxylate-amine complex, as well as by taking into account the optimized DFT data of the configurations [13], are shown in Scheme 3. The simulation was performed on a GPU-based system with large-scale simulations of 179,600 particles. DFT optimization of the equilibrium configuration of functional groups was performed in an aqueous medium.

Scheme 3. Molecular Interactions of Nanoparticles

Carboxylate (A) – Electrostatic/Hydrogen/Van der Waals Interactions – Amine (B)

↓

Energy of complexation: $E_{complex} = E_A + E_B - E_{AB}$

↓

Interfacial mass transfer and liquid microstructure formation

Conclusion

- A comprehensive method for Janus nanoparticle synthesis with controlled morphology and functional integration was developed.
- Novel conceptual mechanisms were proposed, including asymmetric wettability control, self-orienting behavior, and the “nano-anchor” micromechanism.
- High efficiency in interfacial processes and potential for enhanced oil recovery (EOR) were demonstrated.
- The study provides a methodological foundation for future research on multiphase catalytic systems and “smart” functional materials.

Conflict of interest

The authors of this work declare that they have no conflicts of interest.

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