Frontiers in Nanoscience and Nanotechnology

Editorial ISSN: 2397-6527

Editorial: Emerging compositions and functional frontiers in mesoporous materials

Yalin He and Kun Lan*

College of Energy Materials and Chemistry, College of Chemistry and Chemical Engineering, Inner Mongolia University, Hohhot 010021, P.R. China

Introduction

The development of mesoporous materials reflects the progress of nanoscience and technology. Since emerging on the scientific stage in the 1990s, these porous materials with pore sizes ranging from 2 to 50 nanometers serve as bridges between molecular-scale and macroscopic properties, thanks to their precisely controllable nanostructures [1]. They not only embody the core principle of nanotechnology—achieving unprecedented macroscopic properties by manipulating nanoscale structures—but have also become pivotal platform materials driving technological innovation across multiple fields.

Within the framework of nanoscience, the value of mesoporous materials extends far beyond their high specific surface area and ordered pore networks. Essentially, they are assemblies of highly ordered "nanostructural units" (such as micelles and nanoparticles), and their study has profoundly enriched our understanding of self-assembly principles at the nanoscale. From the cooperative self-assembly of soft templates to the nano-casting of hard templates, each breakthrough in these synthetic methodologies deepens our comprehension of material interactions and structural construction capabilities at the nanoscale [2]. More importantly, mesoporous materials serve as ideal "nanoreactors" or "nanocarriers" for other functional nanomaterials—such as metal nanoparticles, quantum dots, and molecular machines—enabling precise control over the size, distribution, and microenvironment of active species. This precisely aligns with nanotechnology's ultimate goal of achieving functional integration and synergistic enhancement.

Their broad application prospects directly reflect nanotechnology's mission to address global challenges. In energy, mesoporous materials serve as catalysts or electrodes, significantly enhancing mass transfer efficiency and reaction activity through their nanopores, thereby advancing the development of next-generation high-efficiency energy conversion and storage systems. In biomedicine, their nanoscale pore sizes are ideally suited for loading drug molecules, genes, or contrast agents, providing powerful nanoscale tools for precise disease diagnosis and treatment. In environmental science, they serve as highly efficient nanoadsorbents or sensors for pollutant capture and detection.

Overview of mesoporous materials

Silica: Mesoporous silica-based materials (such as MCM-41, SBA-15) represent the most extensively studied and technologically mature mesoporous material systems [3]. Their success stems from the mild and controllable hydrolysis condensation rate of silicon-based precursors (e.g., ethyl orthosilicate), enabling efficient synergistic self-assembly with surfactant micelles (e.g., CTAB, P123) to form highly ordered pore structures (e.g., hexagonal, cubic phases). By adjusting the type of templating agent, introducing swelling agents, or performing hydrothermal post-treatment, their pore size, wall thickness, and specific surface area can be precisely controlled. This facilitates the realization of diverse morphologies, ranging from nanospheres and films to core-shell structures.

Owing to the excellent biocompatibility and chemical stability of their amorphous silica frameworks, mesoporous silica-based materials demonstrate significant potential in drug delivery, bioimaging, and adsorption/separation applications. The abundant surface silanol groups facilitate convenient functional group grafting, enabling the introduction of organic groups such as amino or thiol groups to confer specific recognition, catalytic, or responsive release capabilities. Furthermore, the co-condensation of organosilane precursors allows the preparation of periodic mesoporous organosilicas (PMOs), embedding organic functional groups directly into the pore walls to enhance material functionality and stability.

Although mesoporous silica synthesis is well-established, its inherent poor conductivity, limited catalytic activity, and insufficient framework stability in harsh chemical environments remain challenges. Current research frontiers focus on leveraging it as a platform for composites with other nano-functional materials—such as metal nanoparticles, quantum dots, and polymers—to construct smart responsive nanodevices. This approach aims to expand its application boundaries in fields like catalysis and nanomedicine.

Mesoporous metal oxides: (e.g., TiO_2, ZrO_2, WO_2) combine the advantages of mesoporous structures with the unique catalytic, semiconductor, optoelectronic, and magnetic properties inherent to metal oxides, offering broad prospects in energy, sensing, and catalysis [4]. However, their synthesis poses significantly greater challenges than silicon-based materials, primarily due to the difficult-to-control hydrolysis condensation rate of metal precursors, which readily leads to phase separation and structural collapse. Currently, evaporation-induced self-assembly (EISA) stands as the most effective soft-template strategy. Its key lies in employing non-aqueous solvents, chelating agents, or slower-reacting precursors to delay hydrolysis, thereby synchronizing it with the micelle assembly process.

***Correspondence to:** Kun Lan, College of Energy Materials and Chemistry, College of Chemistry and Chemical Engineering, Inner Mongolia University, Hohhot 010021, P.R. China, E-mail: k_lan@imu.edu.cn

Received: October 13, 2025; **Accepted:** November 03, 2025; **Published:** November 10, 2025

To achieve highly crystalline pore walls while preserving mesoscopic structures, researchers have developed two major strategies: First, employing thermally stable block copolymer templates (e.g., KLE, PEO-b-PI) that carbonize into supporting frameworks during thermal treatment; Second, employing the hard-template method (nanocasting) using mesoporous silica or carbon as templates for replication. This approach effectively circumvents assembly challenges and is particularly suitable for synthesizing crystalline metal oxides difficult to prepare with soft templates. Nevertheless, the hard-template method involves cumbersome steps, and structural regularity often diminishes during replication due to volume shrinkage.

Among numerous metal oxides, mesoporous TiO_2 has been most extensively studied. Its morphologies have evolved from powders to complex structures like microspheres with radially aligned pores, single-crystal films, and two-dimensional nanosheets. Such fine structural tuning significantly enhances its performance in dye-sensitized solar cells, lithium-ion batteries, and photocatalysis. Future research will continue to focus on resolving the trade-off between crystallinity and structural stability, while exploring multi-component metal oxides to achieve synergistic functional enhancement.

Metal-organic frameworks (MOFs): MOFs are crystalline porous materials formed by the self-assembly of metal ions/clusters with organic ligands through coordinate bonds [5]. Traditional MOFs predominantly feature micropores, whereas mesoporous MOFs are engineered to combine high crystallinity, large specific surface area, and mesoporous-level mass transfer efficiency. This enables the encapsulation and catalysis of biomolecules such as proteins and enzymes. Two primary strategies exist for mesopore formation: first, "extended building block" design, which involves synthesizing longer organic ligands or employing macrocyclic molecules to directly construct crystalline frameworks with inherently larger pore cavities; second, introducing soft templates (such as surfactant micelles) during synthesis, where co-assembly of micelles with MOF precursors incorporates ordered mesopores into the MOF crystal structure.

Template-assisted synthesis of mesoporous MOFs (or mesoMOFs) represents a major breakthrough in recent years, ingeniously balancing the crystallization kinetics of MOFs with the assembly kinetics of micelles. By selecting specific structure-directing agents (e.g., zwitterionic surfactants) or leveraging salt-ion-regulated Hofmeister effects, researchers have successfully synthesized single-crystal mesoMOFs with worm-like or hexagonal ordered mesopores, featuring tunable particle sizes and pore diameters. This lays the foundation for efficient loading and separation of biomacromolecules.

Conclusion

Despite significant progress, mesoporous MOF research remains in its infancy. Key challenges include long-term structural stability (particularly water stability and mechanical stability), cost-efficiency in large-scale synthesis, and precise control over mesopore positioning and connectivity within crystals. Future advancements will rely on developing novel ligands and assembly mechanisms, while focusing on applying mesoporous MOFs in cutting-edge fields such as advanced catalysis, biomimetic sensing, and targeted delivery—fully leveraging their unique advantages of crystalline pore networks and multiscale structures.

Conflicts of interest

The author declares no conflict of interest.

References

1. Kresge CT, Leonowicz ME, Roth WJ, Vartuli JC, Beck JS (1992) Ordered mesoporous molecular sieves synthesized by a liquid-crystal template mechanism. Nature 359: 710-712.
2. He Y, Li R, Tong H, Wang W, Zhang J, et al. (2025) Emerging compositions in functional mesoporous materials. Chem Soc Rev 54: 6927-6972. [Crossref]
3. Zhao D, Feng J, Huo Q, Melosh N, Fredrickson GH, et al. (1998) Triblock copolymer syntheses of mesoporous silica with periodic 50 to 300 angstrom pores. Science 279: 548-552. [Crossref]
4. He Y, Gao M, Wang W, Zhang J, Li X, et al. (2025) Oriented assembly of unique mesoporous titania conoids for photo-assisted Sn-air battery. Adv Funct Mater 35: 2424225.
5. Lv Z, Lin R, Yang Y, Lan K, Hung CT, et al. (2025) Uniform single-crystal mesoporous metal–organic frameworks. Nat Chem 17: 177-185. [Crossref]