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Original Article

Design, Synthesis and Application of Organic-Inorganic Hybrid Nanocatalysts: Review

Shendge P. R.[1], Shitre G. V.[2], Kele K. V.[3], Solanke M. B.[4]
[1,2,3] Dept. of Chemistry, Vaishnavi Mahavidyalaya Wadwani
[4]Dept. of Microbiology, Vaishnavi Mahavidyalaya Wadwani

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Correspondence Address:
Shendge P. R.
Dept. of Chemistry,
Vaishnavi Mahavidyalaya
Wadwani
Email:
vchemdept@gmail.com

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Abstract

As compared to conventional catalysts, organic–inorganic hybrid nanocatalysts demonstrates considerably higher catalytic activity, increased selectivity, and greater reliability via integrating the unique advantages of both organic and inorganic components. The incredible adaptability of these hybrid systems, which results from the reliability and active-site density of the inorganic framework and the structural flexibility of the organic domain, gets a lot of attention. It is possible to design the organic moieties such as biomolecules, polymers, or functional ligands to provide specific chemical functions, optimize substrate binding, and improve compatibility with various reaction conditions. In addition, the inorganic component such as metal oxides, metal nanoparticles, or porous silica-based materials offers large surface area, mechanical stability, and catalytic centers to support a variety of chemical reactions. Owing to this mutually beneficial interaction, organic–inorganic hybrid nanocatalysts have become suitable for a number of industrial uses and organic synthesis, particularly when high reactivity and precise selectivity are crucial. This review gives an idea about design and synthesis of organic-inorganic hybrid nanocatalysts. It also highlights key strategies such as functional surface modification, ligand integration and core-shell architecture. We are also discussed about catalytic applications in organic synthesis, environmental remediation and pharmaceutical production, with a focus on green and sustainable methodologies. Scalability, long-term stability, and cost-effective production remain to be major challenges that require extra investigation despite significant developments. In the future, it is expected that the combination of artificial intelligence, computational modeling, and bio-inspired design techniques will accelerate the development of next-generation organic–inorganic hybrid nanocatalysts for sustainability and industrially relevant applications.

Keywords: *Organic-inorganic, hybrid, nanocatalysts, ligand, core-shell, green and sustainable methodologies.*

Introduction

Nanocatalysts can enhance the reaction rate, improve selectivity, and reduce the reaction temperature. Therefore, nanocatalysis has gained significant attention[1]. Solid-supported heterogeneous nanoscale catalysts are effective for controlling chemical reactivity and the easy recovery of catalysts, which are novel nanotechnology tools in the modern state-of-the-art catalysis science[2]. Organic-inorganic hybrid nanocatalysts combine the benefits of inorganic materials with organic moieties to create tailored catalytic systems with improved efficiency and stability[3].

Advantage of Organic-Inorganic Hybrid Nanocatalysts

In a hybrid system, the components are highly organized at the molecular and nanoscale levels. These components interact with each other to form a chemical structure[4]. The set of properties of the components and their kinship may result in new properties that determine the properties of the hybrid system[5]. The coordination between organic and inorganic components and the higher surface area and active sites enhance the catalytic activities[6]. The stability of the hybrid system is improved by inorganic components providing structural stability, and organic compounds prevent extreme pH and temperature conditions[7]. These hybrid nanocatalysis are recyclable and can be regenerated by simple washing and mild thermal treatment[8]. In hybrid systems, the reaction conditions are mild, energy consumption is low, waste generation is minimal, and toxicity is low, which follows the principles of green chemistry[9-10].

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Organic functional groups can be designed to enhance enantioselectivity by providing molecular recognition[11].

Classification of Hybrid Nanocatalysts

a. Core-Shell Nanocatalysts
b. Metal-Organic Framework (MOF)-based catalysts
c. Polymer-functionalized nanoparticles
d. Ligand-Functionalized Metal Nanoparticles

Design Strategies for organic-Inorganic Hybrid nanocatalysts

Core-Shell Architecture

In Core-shell structures an inorganic core is protected by organic layer gives better stability and enhance catalytic efficiency.

1. Manpreet Kaur and colleagues developed Pd nanoparticles doped with Mn^{2+} and Mn^{3+} and decorated ZnO/Fe_3O_4 cores for catalytic C-C coupling nitro aromatics reduction and alcohol and hydrocarbon oxidation. The metal manganese ions in two different oxidation state can exerts variable promotional effects in different organic transformation illustrating distinctive nature of manganese ions as dopant[12].

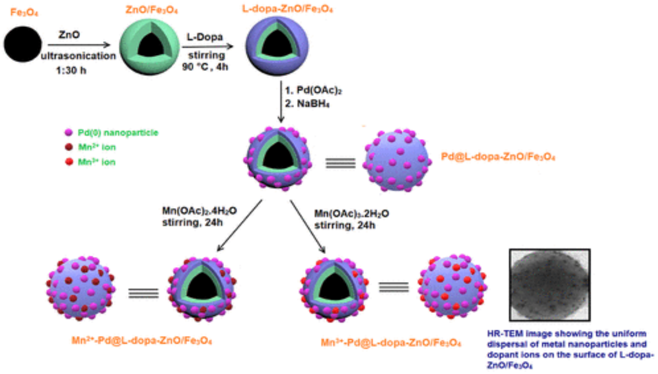

Fig. 1. Schematic Representation of the Synthesis of Undoped and Doped Pd Nano-Catalysts.

2. Reza Eivazzadeh-Keihan *et.al.* synthesized 4h-chromenes using ultrasonic waves, by using core-shell magnetic supramolecular nanocatalysts based on amino-functionalized calix [4] arenes.

An efficient and functional magnetic nanocomposites reveals remarkable efficiency and high yield percentage in shorter reaction time due to sonocatalysis[13].

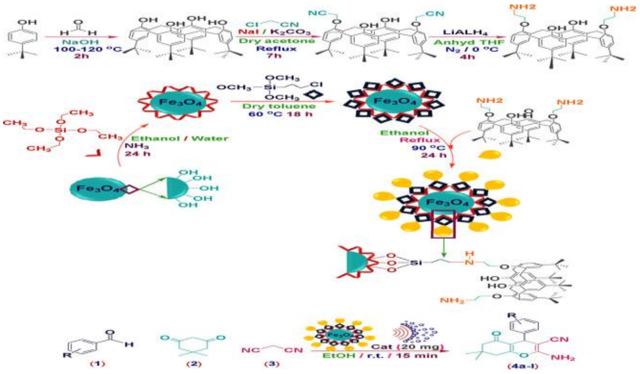

Fig. 2. Preparation of core-shell MNCACAs.

3. Sriparna dutta *et. al.* created created core-shell-structured organic-inorganic hybrid nanocatalysts to quickly synthesize polysubstituted oxazoles by using Tandem oxidative Cyclization Pathway[14].

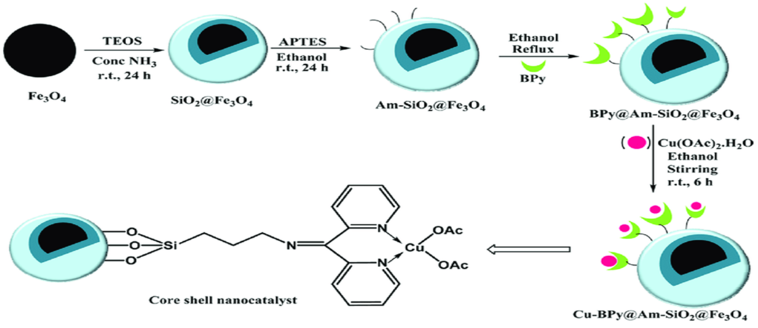

Fig. 3. Synthetic Pathway for Obtaining Cu-BPy@Am-SiO_2@Fe_3O_4 Core–Shell Nanocatalysts.

Metal- Organic Framework (MOF) based Catalysts

In MOF metal ions are incorporated within the organic ligand frameworks, forming highly porous 3D frameworks.

1. Zong-Qun Li *et al.* synthesizes highly porous hybrid materials consisting of metal clusters and organic linkers. At room temperature, high yields of $Cu_3(BTC)_2$ nanocrystals, a 3-D coordination polymer with a 3-D channel system, were produced in short reaction periods (5–60 min)[15].
2. Anirban karmakar *et al.* designed and synthesized Zn and Cd metal organic frameworks functionalized with bifunctional amides were synthesized for one-pot cascade deacetalization–knoevenagel reactions. It act as bifuctional catalysis because MOF contains lewis acid (Zn & Cd) and Lewis basic (amide and free pyridyl groups) sites[16].

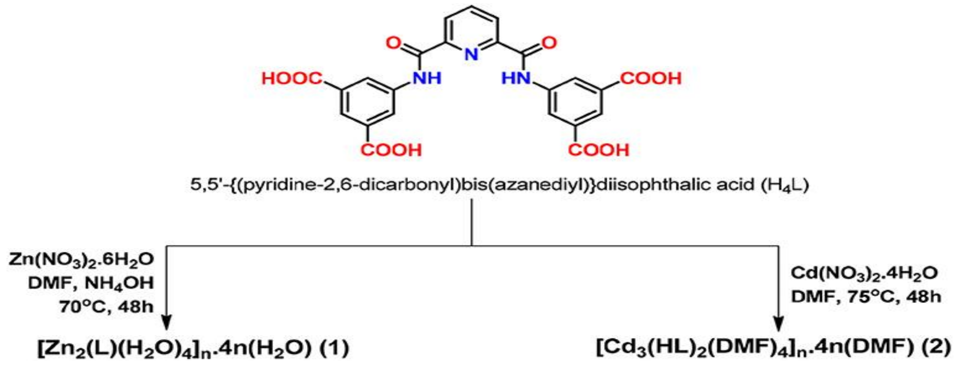

Fig. 4. Synthesis of Zn and Cd metal Organic Frameworks.

Polymer-Functionalized Catalysts

In polymer-functionalized catalysts, organic polymers are covalently or physically grafted onto the surface of inorganic nanoparticles.

1. Molecularly imprinted polymer functionalized silica nanoparticles were developed by Ling Li et al. to separate racemic tryptophan enantioseparation in aqueous solution. The size, shape, and spatial distribution of functional groups in SiO_2@MPS@MIP were substantially similar to those in the template L-tryptophan. Polymer functionalized catalyst demonstrated significant enantiomeric recognition selectivity toward the template[17].

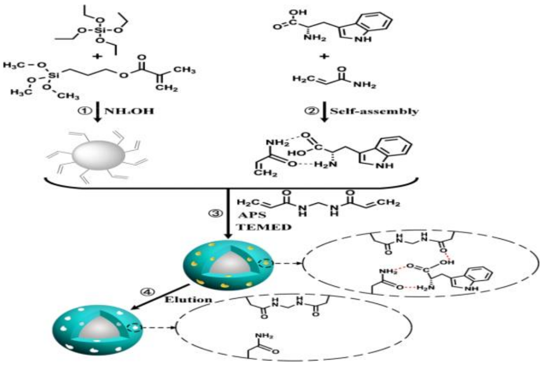

Fig. 5. Schematic representation of the synthetic procedure of SiO_2@MPS@MIP

2. Mahsa Dehghan *et al.* synthesized polymer-functionalized Fe_3O_4/SiO_2-NH_2 using an ultrasonic-assisted technique as a catalyst to selectively oxidize alcohols in a DMSO and water combination to aldehydes and ketones[18].

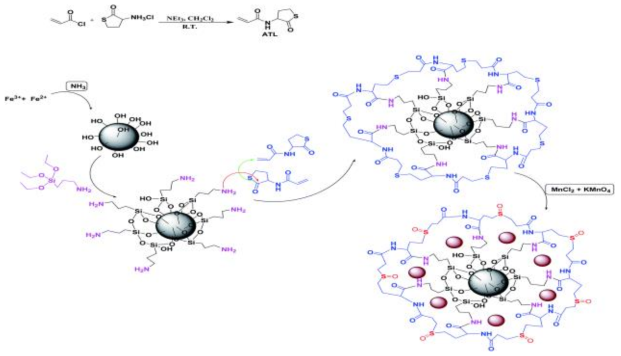

Fig. 6. The schematic pathway for synthesis of $Fe_3O_4/SiO_2/PATL/MnO_2$ nanocatalyst

Ligand Functionalization

It involves metal nanoparticles stabilized or modified by organic ligands preventing aggregation or oxidation of metals and tuning electronic and steric properties to influence catalytic activity and selectivity.

1. Wenlei Zhang *et. al.* synthesized various Pt@UiO-66 composites with organic ligands, including Pt@UiO-66-NH_2, Pt@UiO-66-SO_3H, and Pt@UiO-66. These composites improved steric hindrance and aided in multipathway electron transfer in the selective hydrogenation of linear citronellal. Instead of only facilitating the single-path electron transfer between metal nodes and Pt NPs, the functional groups on organic ligands helped to facilitate the multipathway electron transfer between Pt NPs, metal nodes, organic ligands and MNPs[19].

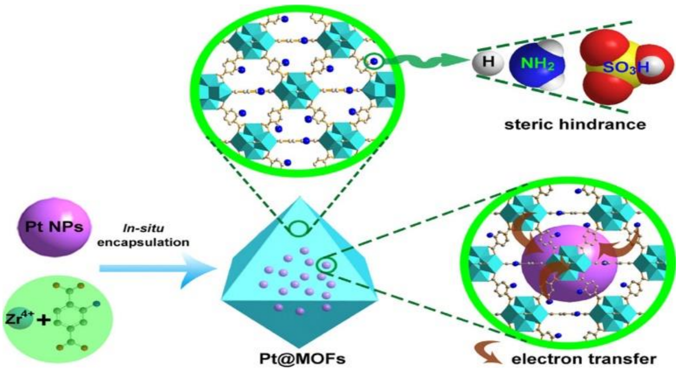

Fig. 7. Schematic Illustration of Functionalized Pt@ UiO-66 Series

2. Naoki Ogiwara *et. al.* produced Pt NCs coated with a water-stable MOF, UiO-66 (Pt@UiO-66), that had various metal ions or functionalized ligands. The catalytic efficacy of the water-gas shift was greatly impacted by the ligand functionalization of UiO-66 [20].

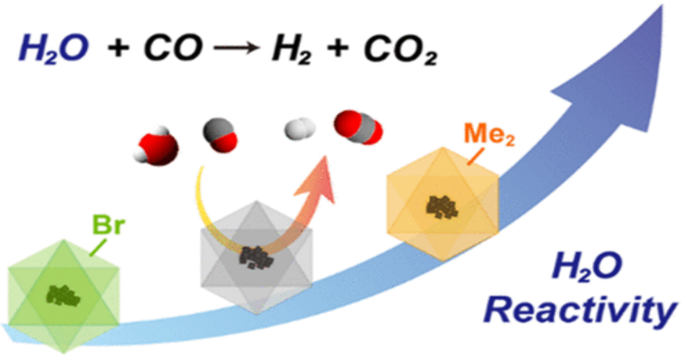

Fig. 8. Catalytic performance of ligand functionalization of UiO-66 in the water-gas shift reaction.

Applications of Organic-Inorganic Hybrid Nanocatalysts

The Organic-Inorganic hybrid nanomaterials are widely used as catalyst due to their high surface area and active sites[21-23].These catalyst shows selective absorption behavior, which makes them useful in chemical separations[24-28]. Porous structure and biocompability allow them to use in drug delivery[29-30], they can absorb, store and release gases for energy and environmental applications [31-35], they have also application in light harvesting and energy conversion[36‾38]. Some hybrid nanocatalysts exhibits conductivity properties, so they are used in sensor and electronic devices[39].

Conclusion

Organic-inorganic hybrid nanocatalysts combine the properties of organic and inorganic components, which enhance the catalytic activity. Advances in core-shell design, polymer functionalization, ligand functionalization, and MOF-based systems have improved catalyst efficiency and stability. These hybrid systems are used for a wide range of chemical transformations.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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