

Review

A Brief Overview of Recent Progress in Porous Silica as Catalyst Supports

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Abstract: Porous silica particles have shown applications in various technological fields including their use as catalyst supports in heterogeneous catalysis. The mesoporous silica particles have ordered porosity, high surface area, and good chemical stability. These interesting structural or textural properties make porous silica an attractive material for use as catalyst supports in various heterogeneous catalysis reactions. The colloidal nature of the porous silica particles is highly useful in catalytic applications as it guarantees better mass transfer properties and uniform distribution of the various metal or metal oxide nanocatalysts in solution. The catalysts show high activity, low degree of metal leaching, and ease in recycling when supported or immobilized on porous silica-based materials. In this overview, we have pointed out the importance of porous silica as catalyst supports. A variety of chemical reactions catalyzed by different catalysts loaded or embedded in porous silica supports are studied. The latest reports from the literature about the use of porous silica-based materials as catalyst supports are listed and analyzed. The new and continued trends are discussed with examples.

Keywords: porous silica; catalyst; heterogeneous catalysis; catalyst support; stability



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1. Introduction

Porous silicas are chemically and thermally stable materials with uniform pore size, pore distribution, high surface area, and high adsorption capacity [1–3]. The size and shape of the porous silica particles as well as the structure of pores on them can be tuned by controlling synthetic parameters like temperature, reaction time, and the amount of silicates/silica source; adjusting the surfactant concentration; changing the calcination conditions; etc. [4,5]. The pore size and its uniformity contribute to the strength of porous silica material [6]. A huge number of reports appear in the literature on silica and porous silica materials and their applications [7–13]. This shows their versatility and use in various technological or industrial applications. In particular, mesoporous silica nanoparticles are useful in several fields of application, such as environmental, biomedical, energy, and as catalyst supports [14]. They are also used in drug delivery [15], vaccine development, biomass conversion, and as catalyst or catalyst supports [16]. Due to the ordered porosity and unique features, they also act as highly efficient nano adsorbents for the adsorption removal of various toxic pollutants [17,18]. These extended applications of porous silica particles are due to the ease of their functionalization of both the internal and external surfaces of their pores with various organic functional groups [19]. The porous silica particles can also be used as a strong support matrix in catalytic applications [20].

The first report about the synthesis of ordered mesoporous silica material was in early 1990 [21]. Recently, there are several modified and new synthetic techniques for

the synthesis of porous silica particles. The newly invented techniques provide some advantages over the old methods. They offer control over synthesis conditions during nucleation and growth process [22]. Due to this, it is possible to produce silica nanoparticles with pore diameters ranging from microporous (below 2 nm) and mesoporous (2–50 nm) to macroporous (above 50 nm) [23]. The most common types of silica materials in the mesoporous pore size range are Mobil Crystalline Materials-41 (MCM-41) [24]; Santa Barbara Amorphous (SBA-15) [25,26] with hexagonal pore structure; and other types such as Hiroshima Mesoporous Material (HMM-33), Technical Delft University (TUD-1), folded sheets mesoporous materials (FSM-16), SBA-16, MCM-48, SBA-11, SBA-12, SBA-16, KIT-5, etc. Table 1 enlists the most common types of porous silica particles with their characteristic features and properties. Figure 1 shows the structures of different types of mesoporous silica nanoparticles. Due to the excellent chemical stability and the possibility of incorporation of various nanomaterials (catalysts), porous silica materials have received increased attention as catalyst supports. Among the various types of mesoporous silica materials mentioned above, MCM-50, SBA-11, and SBA-12 are reported as excellent adsorbent and catalytic supports [27].

Table 1. List of different types of mesoporous silica nanoparticles (MSNs) and their characteristic properties [27].

MSN Family	MSN Type	Pore Symmetry	Pore Size (nm)	Pore Volume (cm ³ /g)
M41S	MCM-41	2D hexagonal	1.5–8	>1.0
	MCM-48	3D cubic	2–5	>1.0
	MCM-50	Lamellar	2–5	>1.0
SBA	SBA-11	3D cubic	2.1–3.6	0.68
	SBA-12	3D hexagonal	3.1	0.83
	SBA-15	2D hexagonal	6–0	1.17
	SBA-16	Cubic	5–15	0.91
KIT	KIT-5	Cubic	9.3	0.45
COK	COK-12	Hexagonal	5.8	0.45
FDU	FDU-12	3D Cubic	10–26	0.66

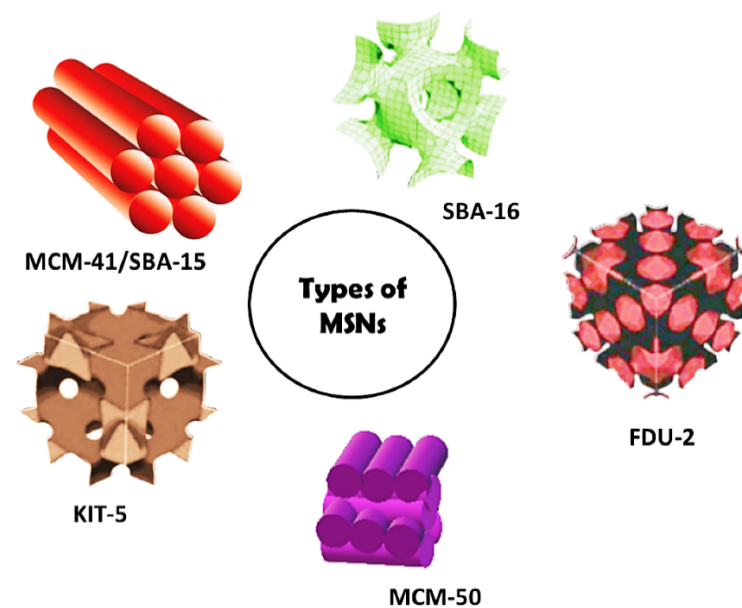


Figure 1. Different types of mesoporous silica nanoparticles. Reproduced with permission from the authors of [27].

The solid or porous silica materials are most commonly synthesized by sol-gel and hydrothermal processes. These methods include the use of reagents such as tetraethoxysilane (TEOS) as a silica source, cetyltrimethylammonium bromide (CTAB) as a templating agent, trimethyl benzene (TMB) as a modulator to tune the pore diameter, and alcohol as a solvent in combination with water [28,29]. The most established way to synthesize the catalyst-immobilized porous silica is using catalyst material as a base in a sol-gel process that will result in densely structured particles impregnated on or inside the highly branched silica network [30]. The composition and pore structure of the catalyst-immobilized porous silica materials can be studied with various characterization techniques such as infrared spectroscopy (IR), X-ray diffraction (XRD), thermogravimetric analysis (TGA), Brunauer-Emmett-Teller (BET), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and nuclear magnetic resonance (NMR) [31,32]. These techniques can be used to conform the formation of siloxane network, porosity, formation, and incorporation of the catalyst particles in the silica matrix. Porous silicas are good catalyst supports because of their inertness, multi-functionalities, and stability in almost all solvents and high catalytic selectivity. The first report of using mesoporous silica in a polymer synthesis catalysis was reported by Aida's group in Japan, which opened a new route for advanced solid supported catalysis [33]. Their ability to catalyze (by virtue of the catalyst loaded) any reaction of alkylation, arylation, or vinylation of various alkenes in organic catalysis makes them an attractive material [34]. Their ability to readily separate from the product after reaction completion is another characteristic feature of porous silicas [35]. Porous silica-based materials have also been investigated as supports for enzymes such as cytochrome C (MW-12k) and showed that the immobilization of enzymes on inorganic material like porous silica is very useful in practical applications [36]. This is a classic example of the potential of porous silicas to improve the stability of biomolecules or an enzyme under extreme conditions. In this brief review, we have presented basic information about porous silica particles and highlighted their use as catalyst supports. The requirements of good catalyst supports are discussed, and the very latest reports from the literature about the use of porous silica-based materials as catalyst supports are enlisted with analysis.

MCM: Mobil Crystalline Materials; SBA: Santa Barbara Amorphous; KIT: Korea Advanced Institute of Science and Technology, COK: Centre for Research Chemistry and Catalysis Mobil Crystalline, FDU: Fairleigh Dickinson University.

2. Catalyst Support Properties and Requirements

Catalyst supports are important to support solid catalysts as they increase the efficiency of the supported metals or metal oxides by acting as a catalytically active center. The support can be chemically inert or it may interact with the active component (actual catalyst). Note that the interactions of the reactants in solid, liquid, or in gaseous forms with the support material must be non-destructive. The interactions of the support material with the active catalyst thereby affect the catalyst activity and selectivity. The support material may not contribute directly to the catalytic reaction process but may contribute indirectly by adsorbing the reactants near the embedded catalysts. The materials used as catalyst supports must show chemical stability, high surface area, as well as capability of dispersing metal or metal oxide particles highly over their surface. This is very important when expensive metals, such as gold, silver, platinum, ruthenium, palladium, etc., are used as the catalysts. Nanoparticles of noble metals are prepared to obtain the catalyst with high surface area and the supports must expose the right sides or maximum surface of the nanomaterials for the chemical reaction to occur. Supports give the catalyst its physical form, texture, mechanical resistance, and certain activity particularly for bifunctional catalysts. The surface chemical (functional groups) and physical properties of surfaces affect the performance of the supported metals. By keeping in mind these requirements, various oxides and carbon compounds are being used as catalyst support materials. Among all materials, silica (SiO_2) acts as an excellent catalyst support material due to its outstanding chemical and physical properties. The porosity plays an important role in increasing the

efficiency of catalyst supports. The shape as well as the size of pores of the support have an important effect on the activity and stability of embedded catalysts. Metal nanoparticles supported on porous silica-based supports exhibit higher catalytic activity arising from the higher accessibility of the active sites. A variety of porous silica particles are available as catalyst supports. Table 2 lists the main types of porous silica materials used as catalyst supports and their characteristic properties. The chemical inertness and high stability make these materials ideal catalyst supports. Figure 2 shows a representative example of how nickel nanoparticles are loaded or trapped inside different types of mesoporous silica-based catalyst supports. The different arrangements of the embedded catalyst inside the porous silica are clearly visible.

Table 2. Comparison of the properties of various porous silica particles.

Full Name	Santa Barbara Amorphous Type 15	Santa Barbara Amorphous Type 16	Mobil Composition of Matter No. 41	Mobil Composition of Matter No. 48	Hexagonal Mesoporous Silica
Short name	SBA-15	SBA-16	MCM-41	MCM-48	HMS
Structure directing agent	Pluronic 123 (non-ionic)	Pluronic F127 (non-ionic)	CTAB (cationic)	CTAB (cationic)	Amines (non-ionic)
pH at synthesis	Acidic (pH ~ 1)	Acidic (pH ~ 1)	Basic (pH ~ 11–13)	Basic (pH ~ 11–13)	Basic (pH ~ 9)
Features	Hexagonal pores, 2D array, <i>p6mm</i> symmetry, channels interconnected by small micropores	3D cubic arrangement connected by spherical cavities, <i>Im3m</i> space symmetry	1D mesopores, <i>p6mm</i> hexagonal, absence of interconnected pores	<i>la3d</i> 3D cubic continuous pore arrangement	Sponge-like particles, warm-hole mesostructured framework
Pore diameter	Uniform and larger pore diameter (4–30 nm) facilitating easy diffusion	Similar pore diameter values but nonuniform mesopores	Smaller pore diameter (1.5–10 nm) hindering the diffusion of substrates	Smaller pore diameter (2–3 nm) hindering the diffusion of substrates	Smaller pore diameter than SBA-15 (2–10)
Range of surface area	Higher surface area (~1000 m ² /g), high surface area to volume ratio	Comparable surface area values to SBA-15	Lower surface area (~800 m ² /g)	Higher surface area (~1100 m ² /g)	Surface area (800–1000 m ² /g)
Stability	Thick walls (up to 9 nm) and hence more thermally stable	Thick walls comparable to SBA-15	Thin walls (0.5 nm) and thus poor hydrothermal stability	Thin walls and hence comparatively less thermally stable	Less ordered structure but comparable stability

There are some important points that need to be considered both during the post-synthesis loading of the catalysts and in situ synthesis and loading of the catalyst particles on the porous silica-based supports. During in situ synthesis (generation), the catalyst particles get embedded inside the porous catalyst supports and may improve the overall mechanical stability of the porous support matrix. Instead, the post-synthesis loading of the catalyst particles inside the porous supports may pose some problems such as pore blocking (as seen in some images in Figure 2). Therefore, the size of the catalyst particles during post-synthesis immobilization must be smaller than the pore size. The blocking of the pores will prevent the reactant in various states to enter the pores and the overall conversion will be low. The covalent immobilization of catalyst particles during the post-synthesis catalyst loading is also essential. The catalyst particles can be held by strong bonds between the support and the surface of the catalyst. However, there is high likelihood of compromising the catalyst surface for surface modification and subsequent covalent immobilization reactions, which will affect the efficiency of the catalyst. The

percentage of loading (with respect to the weight of the porous catalyst support) of the catalyst can greatly affect the stability of the support matrix as well as the catalytic efficiency. An optimum loading of the catalyst is necessary for efficient performance of the catalyst in the reaction to be catalyzed. The shape of the pores available or created on the porous matrix/particles also play an important role in determining the efficiency of the material. If the shape of the catalyst particles and the pores is the same, then there is great possibility of proper filling of the pores by catalyst particles. The post-synthesis covalent immobilization of the catalyst and in situ synthesis and deposition of the catalyst on porous silica-based supports guarantee high stability of the material.

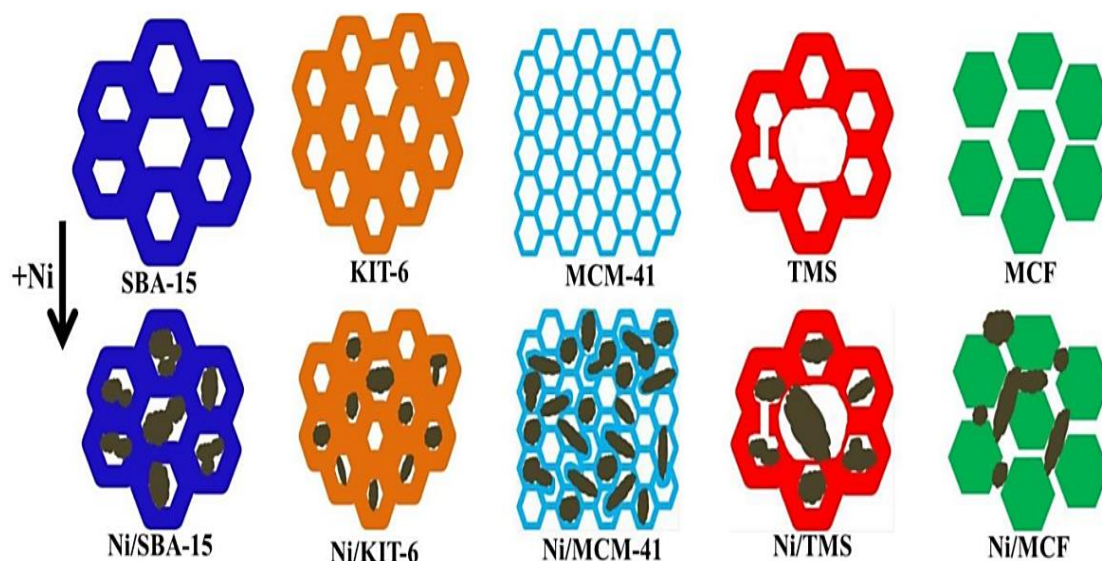


Figure 2. Schematic of the confinement effect on the Ni nanoparticles trapped inside the channels of supports. Reproduced with permission from the authors of [37].

3. Types of Reactions

The versatility and stability of the porous silica-based catalyst supports are evidenced by a variety of chemical reactions catalyzed by different catalysts supported on them. The porous silica-based catalyst supports are used in the reactions such as aerobic oxidation of alcohols (1-phenylethanol and benzyl alcohol) [38]; oxidation of methane to methanol [39,40], propene [41], benzene, benzyl alcohol [42], and toluene [43]; oxidative removal of 4,6-dimethyldibenzothiophene [44]; photooxidation of CO [45]; CO oxidation at low temperature [46–48]; organic oxidation of 1,2-dichloropropane [49,50]; photodegradation of methylene blue [51]; CO₂ adsorption [52–54]; hydrodeoxygenation of anisole [55]; esterification to produce biofuels [56,57]; biodiesel production from palm acid distillate [58]; biofuel upgrade (hydrocracking of camelina FAMES) [59]; model transesterification reaction (ethyl acetate + methanol = methyl acetate) [60]; dehydration of glycerol [61]; hydrodesulfurization [62]; decomposition of N₂O [63] and formic acid (HCOOH \leftrightarrow H₂ + CO₂) [64]; cycloisomerization of alkyenoic acids to alkylidene lactones [65]; coupling reactions (clean synthesis) [4,66,67]; carbon-carbon bond forming reactions [68]; removal of exhaust gas pollutant [69]; waste water treatment [70]; polymerization of olefins [71–73]; biodegradable polymer synthesis [74]; hydrocracking of pyrolyzed α -cellulose [75]; dehydration transfer hydrogenation [76]; selective hydrogenation of butadiene [77]; hydrogenation of methanol [78]; p-nitrophenol to p-aminophenol [79]; dehydrogenation [80–84]; CO₂ to methanol (CH₃OH) [85]; epoxidation of styrene [86–88]; cyanosilylation [33]; reduction of N₂ to ammonia [89]; bromate [90]; photocatalytic water oxidation [91]; photocatalytic degradation and removal of Cr(VI) and methylene blue [92]; photocatalytic hydrogen evolution from water [93]; catalytic transfer hydrogenation for the synthesis of γ -valerolactone [94,95];

Friedel-Craft alkylation reaction of aromatic compounds [96]; addition of carbon heteroatom bond formation [97]; and soot combustion [98].

A classic example of use of porous silica as catalyst supports is shown in Figure 3. It shows highly monodispersed palladium nanoparticles immobilized in three-dimensional dendritic mesoporous silica used as catalyst in Suzuki-Miyaura C-C cross-coupling. Instead, Figure 4 shows AuPt alloy yolk@shell hollow nanoparticles and their incorporation into hollow interiors of a mesoporous silica microspheres based on a rapid aerosol process. The AuPt@SiO₂ spheres showed excellent catalytic performance in the epoxidation of styrene with conversion and selectivity of 85% and 87%, respectively. Note that the various reactions mentioned above include different reactions conditions and states of the reactants, solvents, and other chemicals, and the silica-based catalyst support withstands all those conditions, proving its chemical stability, which is the prime requirement of the catalyst support as mentioned above.

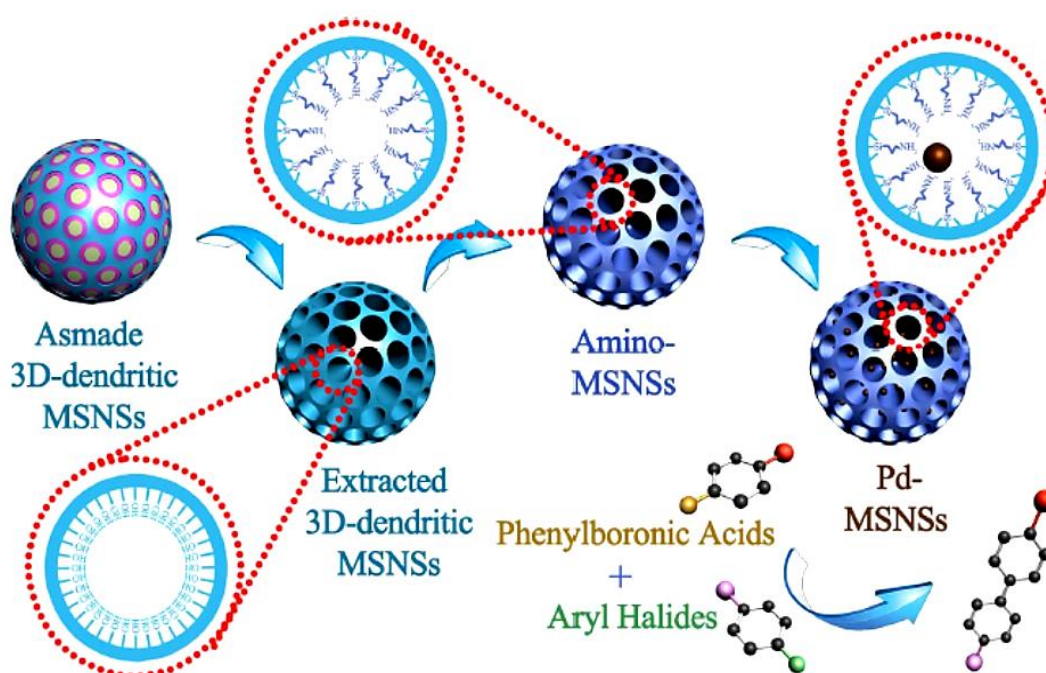


Figure 3. Synthesis and catalytic process of highly monodispersed palladium nanoparticles immobilized in three-dimensional dendritic mesoporous silica. Reproduced with permission from in [99].

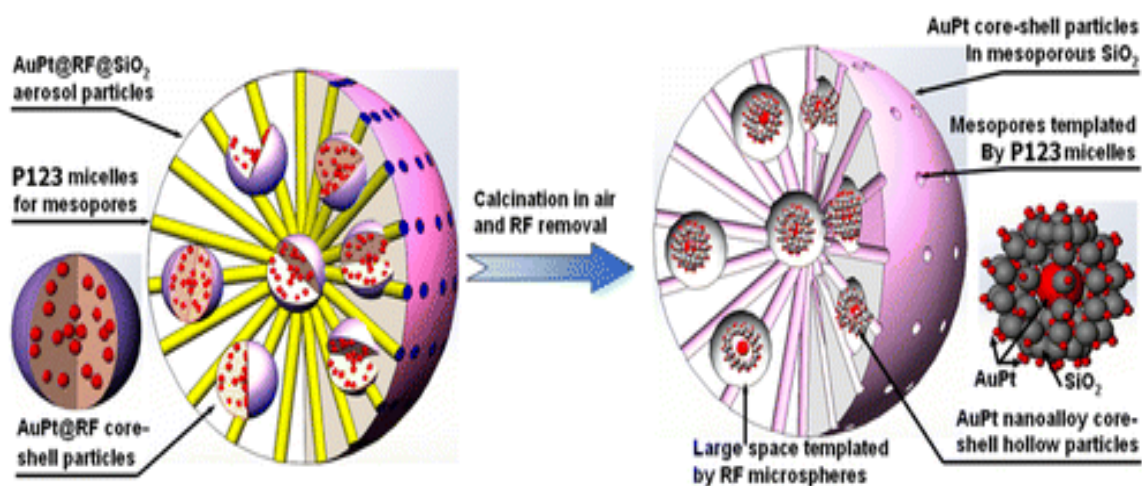


Figure 4. AuPt nanoalloy yolk@shell hollow particles in ordered mesoporous silica microspheres. Reproduced with permission from the authors of [100].

4. Recent Reports, Analysis and Trends

The very latest reports from the literature about porous silica-based catalyst supports are enlisted in Table 3 with the name of the catalyst material and reactions catalyzed. Observation of the entries in Table 3 reveals some trends about the use of porous silica-based materials as catalyst supports. Due to its simplicity and efficiency to produce monodispersed porous silica particles, the sol-gel technique remains the most common synthesis technique to obtain the porous supports. The trend of in situ synthesis and loading of the catalysts in the same synthesis conditions is also observed. The soft (easily degradable) template approach is the preferred technique to generate the porosity, and it is observed in most of the reports. Instead, a variety of different catalysts, such as noble metal nanoparticles, bimetallic nanoparticles, composite nanoparticles, alloys, noble metal, composite material nanocrystals, etc., are embedded in the porous silica-based supports. The pore sizes were tuned as per the sizes of various catalysts embedded in the materials. A variety of new reactions are added to the previously reported reactions as pointed out above. Most of the latest works also cover the studies of recyclability of the catalysts immobilized on silica-based catalyst supports, this proves the good hydrothermal or solvothermal (considering the fact that aqueous as well various solvents are used in the various reactions carried out) stability of the porous silica network. This is important from a technology and cost point of view. All the reports suggest the improved catalytic performance of the catalysts in various chemical reactions upon their immobilization on the porous silica-based catalyst supports. In addition to mere catalyst supports, some of the very interesting works report the chemical reactions catalyzed by porous silicas or by functional (that is organic functional group bearing) porous silica nanoparticles.

Table 3. Summary of the latest reports from the literature about the use of porous silica-based catalyst supports.

Sr. No.	Material	Type of Synthesis	Catalyst	Chemical Reaction	Ref.
1.	Core-shell structured magnetic silica.	Sol-gel	Bronsted acid	Transesterification of soybean oils, low-quality oils to biodiesel	[101]
2.	Chondroitinase ABC (I) on red porous silicon nanoparticles	Electrochemical etching	chondroitinase	Biological enzyme catalysis reaction	[102]
3.	Mesoporous-silica-supported metal nanocatalysts	Sol-gel	Metal nanocatalyst (Ag, Pd, amines)	Dehydrogenation of formic acid for Hydrogen generation ($\text{HCOOH} \rightarrow \text{H}_2 + \text{CO}_2$)	[103]
4.	Mesoporous silica (SBA-15, MCM-41)	Sol-gel	Palladium and platinum nanoparticles	Organic synthesis alcohols, carboxylic acids, and esters	[104]
5.	Mesoporous silica spheres and nanocapsules	Soft and hard dual template	Sulfonic acid	Biomass valorization catalysis, conversion of cellobiose into glucose	[105]
6.	Silica nanoshell ($\text{Pd}/\text{Fe}_3\text{O}_4@h\text{-SiO}_2$)	Sol-gel	Pd nanocrystals	Biorthogonal Organic Synthesis, carbocyclization reactions, converting a range of non-fluorescent substrates to fluorescent products	[106]
7.	Mesoporous fumed silica	Sol-gel	Palladium, Cobalt, Nickel, and Copper	Suzuki cross-coupling (SCC) reactions (C-C bond forming reaction) Cross-coupling reaction between bromobenzene with benzenboronic acid give biphenyl	[107]

Table 3. Cont.

Sr. No.	Material	Type of Synthesis	Catalyst	Chemical Reaction	Ref.
8.	Mesoporous MoO ₃ /SiO ₂ nanosphere networks	Self-assembly	MoO ₃	oxidative desulfurization of Dibenzothiophene (DBT)	[108]
9.	Silica	Sol-gel	IrO ₂	Photodegradation of methylene blue	[109]
10.	Dendrimer-like Porous Silica Nanoparticles (DPSNs)	Template-mediated self-assembly	Cu-BTC MOFs	Catalytic aerobic epoxidation of olefins, cyclooctene to cyclooctane oxide	[110]
11.	Mesoporous Silica (Fe@silica)	Sol-gel and Hydrothermal	Iron	Oxidation	[82]
12.	Silica (CuO@SiO ₂)	Sol-gel	Cu nanoparticles (NPs)	Cu-catalyzed organic transformations, C-C bond formation, reduction of organic dye	[111]
13.	Mesoporous silica matrix (MMS)	Direct growth technique	Hongkong University of Science and Technology (HKUST-1) (Cu ₃ (BTC) ₂ , BTC $\frac{1}{4}$ benzene-1,3,5-tricarboxylate) nanoparticles	Condensation reaction, Friedlander reaction between 2-amino-5-chlorobenzophenone and acetylacetone and Henry reaction nitroaldol condensation between nitromethane and 4-nitrobenzaldehyde	[112]
14.	Functionalized mesoporous SBA-15, SBA-16, MCM-41, MCM-48	Sol-gel	Metal nanoparticles (Ti, V, Cr, and Mo)	Catalytic transformation, Dry Reforming of Methane (DRM) reaction as CH ₄ + CO ₂ → 2H ₂ + 2CO	[33]
15.	Porous SiO ₂ (Pt@HS-SiO ₂ PL)	So-gel	Platinum Nanoparticles	Hydrogenation of alkenes (decene to decane) and nitroarenes to amino phenol	[113]
16.	Silica (SiO ₂) powder	Sol-gel	Diethylenetriamine	Knoevenagel reaction (carbon-carbon (C-C) coupling).	[114]
17.	Biosilica Microparticles	Diatom (<i>Thalassiosira pseudonana</i>)	Horseradish peroxidase (HRP), glucose oxidase, Gold nanoparticles	Biological enzyme catalysis reaction of <i>T. pseudonana</i> , Oxidation of glucose.	[115]
18.	Folic acid-functionalized dendritic fibrous nano-silica (FA-KCC-1-NH ₂) (FA = Folic acid, KCC-I = fibrous nano silica)	Hydrothermal	KCC-1-NH-FA nanoparticles	Amidation of carboxylic acids with amines	[116]
19.	Monodisperse mesoporous silica microspheres (M-MSMs)	Sol-gel	Au Nanoparticles	Reduction of 4-nitrophenol (4-NP) to 4-amino phenol	[117]
20.	CaSiO ₃ -SiO ₂ powder	Co-precipitation method	CaSiO ₃ (Na ₂ O·nSiO ₂)	Decomposition of isopropyl alcohol, dehydrogenation of the alcohol producing acetone	[118]
21.	ReO ₃ /SiO ₂ , silica matrix	Sol-gel	ReO ₃ nanoparticles	Photodegradation of Blue Methylene	[119]

Table 3. Cont.

Sr. No.	Material	Type of Synthesis	Catalyst	Chemical Reaction	Ref.
22.	Porous silicon dioxide (SiO ₂) and carboxyl-functionalized carbon nanotube (PtIrNi/SiO ₂ -CNT-COOH)	Sol-gel	PtIrNi alloy nanoparticles	Electrochemical Ammonia Oxidation reaction (AOR)	[120]
23.	Expanded mesoporous silica (EMSN)-encapsulated Pt nanoclusters.	Sol-gel	Pt nanoclusters	Artificial enzymes for tracking hydrogen peroxide secretion from live cells	[121]
24.	Microporous silica microcapsules	Gas-in-water-in oil emulsions (g/w/o)	Microporous silica microcapsules	Ostwald ripening, generation of gas-in-water-in-oil emulsions	[122]
25.	Pt-loaded ZSM-22/MCM-4 (Pt-MES)	Sol-gel	Bronsted acid, Pt nanoparticles	N-alkane isomerization for refinery process by converting the petroleum into the gasoline with high quality and the diesel	[90]
26.	Organo-amine-functionalized castor oil templated mesoporous silicas	Valorization of rice husk	Amine groups	Biodiesel synthesis, transesterification of model C4-C12 triglycerides (TAG) to fatty acid methyl esters	[123]
27.	TEMPO-functionalized mesoporous silica particles, MCM-41 and SBA-	Co-condensation	(2,2,6,6-tetramethylpiperidin-1-yl) oxyl (TEMPO)	Heterogeneous oxidation (oxidation of alcohols to aldehydes), Knoevenagel condensation (C-C bond formation)	[124]
28.	Silica-encapsulated core-shell Co@SiO ₂	Hydrothermal	Cobalt	Fischer-Tropsch synthesis (FTS)	[125]
29.	Porous silica	Sol-gel	Gold nanoparticles	Biomedical, catalytic, and optical properties	[14]
30.	Palladium Nanocatalysts Encapsulated on Porous Silica @ Magnetic Carbon-Coated Cobalt Nanoparticles	Sol-gel	Palladium nanoparticles	Sustainable hydrogenation of nitroarenes to aniline, alkenes and alkynes	[126]
31.	SBA-15-based composites (X@SBA-15)	Impregnation and hydrothermal methods	Transition metals/metal oxides and nanocarbons	Water decontamination by advanced oxidation processes	[25]
32.	Mesoporous silica	Sol-gel	Ni-Co bimetallic hydroxide particles	Urea oxidation reaction	[127]
33.	Porous silica nanotubes loaded Au nanoparticles (SiO ₂ @Au@SiO ₂ NTs)	Sol-gel	Gold nanoparticles	Catalytic reduction of 4-Nitrophenol to 4-amino phenol	[128]
34.	Self-propelled mesoporous silica nanorods (MSNRs)	Sol-gel	Iron oxide (Fe ₂ O ₃) nanoparticles	Catalytic decomposition of hydrogen peroxide by a sputtered Pt layer	[129]
35.	Porous silica	Self-assembly	Metal and alloy nanoparticles (Au, Ag, Pd, Ag/Pd)	Biom mineralization, reduction of 4-nitrophenol to 4-amino phenol	[130]

Table 3. Cont.

Sr. No.	Material	Type of Synthesis	Catalyst	Chemical Reaction	Ref.
36.	A novel and yolk/shell nanoreactor catalyst (H-Fe ₃ O ₄ @h-CuO@m-SiO ₂)	Hydrothermal	CuO-nanoparticles	A3 coupling reaction of alkynes, aldehydes, and amines	[131]
37.	Micron-sized, spherical SiO ₂	Mechanochemical	Spherical silica	Polyolefin catalyst production	[132]
38.	Ni@SiO ₂ core-shell nanocatalysts	Sol-gel	Ni particles	Catalytic oxidation of CH ₄ to CO ₂	[133]
39.	Hollow SiO ₂ spheres	Template synthesis	Au nanoparticles	Catalytic Microreactors, reduction of 4-nitrophenol to 4-aminophenol	[134]
40.	Monolacunary Keggin-type [PW11O39] 7-(PW11) heteropolyanion SBA-15 (PW11@TMA-SBA-15)	Sol-gel	N-trimethylammonium (TMA)	Oxidative desulfurization of organosilica composite	[135]
41.	Porous silica	Sol-gel	Ni nanocatalyst	Thermal gasification of waste biomass	[136]
42.	Macroporous SiO ₂	Sol-gel	Ag ₂ O, Na ₂ O or K ₂ O	Soot combustion reactions, gas-solid-solid reactions	[137]
43.	Aminopropyl functionalized mesocellular foam silica (MCF)	Sol-gel	Penicillin acylase	6-aminopenicillanic acid production, biocatalytic transformation	[138]
44.	TiO ₂ /SiO ₂ /C nanofiber mat, SiO ₂ nanoparticles	Calcination	TiO ₂ /SiO ₂ /C	Photocatalytic degradation of organic pollutants (rhodamine B and 4-nitrophenol) in water	[139]
45.	Alumina-coated silica nanoparticles (AlO-SiO NPs)	Sol-gel	Alumina	Surface reactions	[140]
46.	mesoporous g-C ₃ N ₄ /SiO ₂ material	Sol-gel	Carbon nitride (g-C ₃ N ₄)	Photodegradation of rhodamine B (RhB) under visible light	[141]
47.	Mesoporous silica material KIT-6	Template synthesis	Transition metals	Electrocatalytic hydrogen evolution reaction	[142]
48.	Pd/SiO ₂ and Fe/SiO ₂	Sol-gel	Metallic (Pd catalysts) or metallic oxide (Fe catalysts) nanoparticles	Pd/SiO ₂ Hydrodechlorination of 2,4,6-trichlorophenol (TCP) in water, Fe/SiO ₂ materials degrade phenol	[143]
49.	Bimodal porous silica	Sol-gel	NiO	Phenol to cyclohexanol	[144]
50.	Mesoporous silica materials (SBA-15 and MCM-41)	Sol-gel	Phosphonic and phosphoric acid esters	Asymmetric aldol reaction (C-C bond formation)	[145]
51.	Mesoporous silica (SBA-15)	Sol-gel	Laccase	Enzyme aggregate (E-CLEA) potential in phenol removal	[146]
52.	Novel hollow-Co ₃ O ₄ @Co ₃ O ₄ @SiO ₂ multi-yolk-double-shell nanoreactors	Sol-gel	Metals (Pd, Pt, Ru, Rh, and Au) and metal oxides.	CO Oxidation	[147]

Table 3. Cont.

Sr. No.	Material	Type of Synthesis	Catalyst	Chemical Reaction	Ref.
53.	Ordered mesoporous silicas (MCM-41)	Sol-gel	Aluminum	Hydro isomerization and Friedel-Crafts alkylation of benzene with benzyl alcohol	[148]
54.	Colloidal mesoporous silica nanoparticles (LP-MSNs)	Co-condensation	Alkyne-functionalized	Colorimetric reaction of guaiacol (2-methoxyphenol), hydrolysis of 4-nitrophenyl acetate (NPA) by LP-MSN-CA	[149]

5. Conclusions

This brief overview pointed out the importance of porous silica as catalyst supports. A huge number of reports in the literature on this topic prove the versatility and efficiency of porous silica as catalyst supports. A careful observation of the latest reports showed that some previous trends about the synthesis of porous silica supports and in situ generation and immobilization of the catalysts are continued. A variety of new, bimetallic, composite and functional nanocatalysts are embedded or immobilized on the porous silica nano and microparticles to efficiently catalyze various reactions. The research in this field will proceed in future along following main directions.

Development of functional silica-based porous particles embedded with various catalyst nanoparticles where synergic effects of the various organic functional groups grafted on the supports and the catalyst will assist the chemical transformations.

Further development and optimization of single step or in situ (or minimum steps) methods for the functionalization of the silica-based porous supports as well as synthesis and immobilization of the catalysts.

Development of the large-scale production methods for already reported various composite nanoparticles (catalyst) embedded in porous silica particles.

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