Journal of Composites and Compounds 6(2024) 1-6

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Journal of Composites and Compounds

Innovative nano catalysis techniques: Transforming heterogeneous and homogeneous

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A B S T R A C T

In response to pressing environmental, energy, and sustainability challenges, nanotechnology-driven catalysis is emerging as a transformative approach. Advancements in nanomaterials, especially inorganic nanoparticles, have spurred the development of ecofriendly, efficient catalysts capable of operating in different applications like environmental remediation, energy conversion and storage, pharmaceutical, and biodiesel production. Their high surface area and unique properties such as nanomagnetism and photocatalytic activity, make them versatile for both homogeneous and heterogeneous applications, offering faster reactions and potential cost savings. Nano-catalysis is rapidly progressing as a vital scientific and industrial field, promising sustainable solutions across sectors.

A R T I C L E   I N F O R M A T I O N

Article History:
Received 28 February 2024
Received in revised form 29 May 2024
Accepted 03 June 2024

Keywords:
Nanotechnology
Nano catalysis
Heterogeneous
Homogeneous
Sol-gel

Table of Contents

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https://doi.org/10.61882/jcc.6.2.4

1. Introduction

Nano-materials are crucial across many fields, from research to practical applications in electronics, sensors, catalysts, and energy. They serve as sustainable alternatives to traditional materials, functioning as durable, high-surface-area catalysts and supports. The tiny particles increase exposed surface area, boosting catalyst contact with reactants and mimicking homogeneous catalysts [1, 2]. Additionally to their high surface area, they have other unique properties such as nanomagnetism and photocatalytic activity, make them versatile for both homogeneous and heterogeneous applications, offering faster reactions and potential cost savings [3, 4].

Nanoscience's potential extents nearly all fields e.g., medicine, electronics, manufacturing, fashion, especially through nanocrystal catalysts. Their high surface-to-volume ratio makes nanocrystals highly reactive and tunable, enabling faster reactions by lowering activation energy or improving reactant interaction. Their small size (10–80 nm) and unique properties make nanocatalysts more effective than traditional ones, leading to more efficient, environmentally friendly chemical processes [5].

Nanoparticle catalysis has long been explored with elements like aluminum, iron, and titanium dioxide [3]. Although their high surface area boosts reaction rates, the specific shape, structure, and composition of nanocatalysts also influence their activity. Tailoring these features enhances selectivity and resilience, enabling more resource-efficient, energy-saving, and eco-friendly industrial chemistry. Nanoparticles' heterogeneity causes variable catalytic activity, but understanding their physical properties and fabrication methods allows the design of highly effective nanocatalysts for diverse applications [5, 6].

This review covers foundational concepts in nano catalysis, synthesis methods, types, and applications, including environmental, energy, pharma, and biofuels, and highlighting recent innovations and future prospects in this critical field.

2. Fundamentals of nano catalysis

The development of advanced catalysts aims to produce high-value products cost-effectively, increase energy efficiency, meet strict environmental standards, and reduce reliance on precious metals [5].

2.1. Definition and characteristics

In chemistry, a catalyst is a substance that speeds up or facilitates a chemical reaction without undergoing any permanent change itself. This process is called catalysis. Catalysts can enhance the reaction rate and improve its selectivity, meaning they help the reaction proceed more efficiently and with desired outcomes. Essentially, the catalyst interacts with the reactants, inducing certain changes in the reaction pathway, but remains unchanged after the process. Despite their lower mass compared to raw materials, catalysts play a crucial role in the reaction. Choosing the right catalyst is vital for successful outcomes [2]. Recently, nanoparticles have become effective catalysts, thanks to their active sites composed of metal atoms, metal ions, and the presence of pores around these sites. It is believed that the next wave of catalysts will be nanocatalysts, which are already involved in many chemical processes and are expected to shape future advancements [2, 7].

Catalysts accelerate reactions by providing active sites; reducing particle size enhances this effect. Modern catalysts often involve nanometer-scale particles on specialized supports, with ongoing research focusing on how particle size impacts catalytic performance beyond surface area alone [2].

Nano catalysis is characterized by high activity and selectivity, excellent stability, ease of separation, energy efficiency, and atom economy [8]. The transition from bulk to nanocatalysts can alter product selectivity, although the underlying reasons remain unclear. Recent experiments by Costentin and Savéant suggest that this may result from the interaction between chemical reactions such as reactant conversion, intermediate formation, and product release and the transport of species to the catalyst surface. By modeling the reduction of hydrogenocarbonate ions on metals like Pd or Pt, they identified key parameters that influence selectivity. Their findings also show that the product distribution depends on the diffusion layer thickness, which varies with scale, leading to significant, and sometimes reversible, changes in selectivity under different conditions. While chemical reactivity was often considered the main factor, they emphasize that short-distance transport effects play a crucial role in determining product outcomes [6].

2.2. Mechanisms of catalysis at the nanoscale

Insights into nanocatalysis come from understanding how intrinsic nanomaterial properties affect their catalytic behavior. These include: (i) Bond-related factors like lattice constants and surface relaxation, (ii) Cohesive energy-related aspects such as stability, phase transition temperatures, and atomic mobility, (iii) Properties tied to electronic band structures, like band gaps and energy levels, (iv) Mechanical and magnetic attributes, including surface energy, strength, and magnetic behavior. Understanding these intrinsic factors helps in designing nanomaterials with optimal catalytic performance [8]. Fig. 1 illustrates fundamental properties of nanocatalysts influencing their catalytic performance.

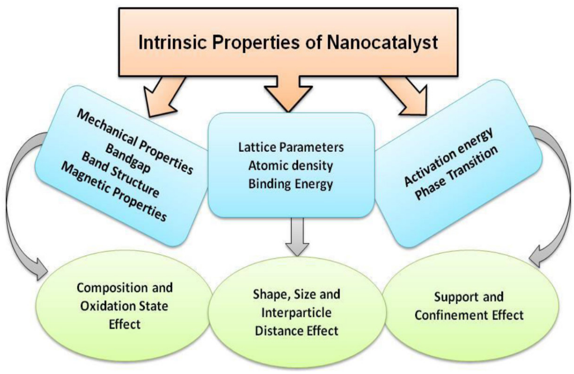

Fig. 1. Fundamental properties of nanocatalysts influencing their catalytic performance [3].

For example, it is suggested that the interaction between Regge resonances and Ramsauer–Townsend minima in the electron elastic cross sections of Au and Pd atoms, combined with their high electron affinities, underpins the remarkable catalytic performance of Au nanoparticles. This mechanism explains why Au–Pd hybrids outperform individual Au or Pd in catalyzing H_2O_2, aligned with recent findings. The study employs a recent complex angular momentum approach to electron-atom scattering to support this explanation [9].

3. Synthesis techniques for nano catalysts

Nanocatalysts are produced mainly via two methods: top-down, which breaks down bulk materials into nanoscale particles (using techniques like etching and sputtering), and bottom-up, where molecules or atoms assemble into nanostructures (through processes such as sol–gel, chemical reduction, or green synthesis). Both rely on controlled kinetics to regulate nanoparticle size and shape [10]. Fig. 2 shows diverse synthesis techniques and the resulting shapes of nanoparticles [10].

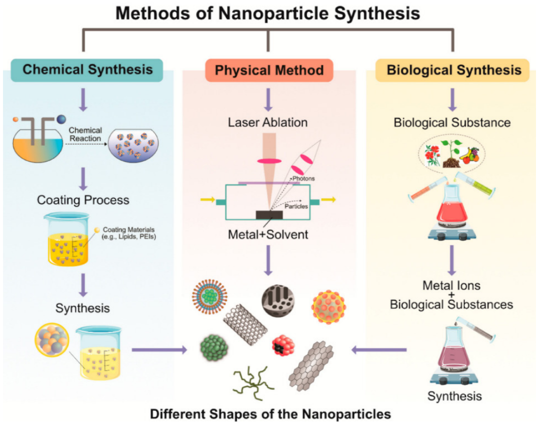

Fig. 2. Diverse synthesis techniques and resulting shapes of nanoparticles [10].

3.1. Sol-gel method

The sol–gel method involves dissolving precursors (like metal alkoxides) to form a gel, which is dried, ground, and calcined to produce nanomaterials, especially metal oxides. It's cost-effective, enables precise composition control, and finds uses in ceramics, electronics, energy devices, and biosensors [11, 12]. For example, Sajjadi et al. [13] created Ni-Co/Al_2O_3-MgO-ZrO_2 catalysts, with ZrO_2 improving activity and stability in methane reforming. Wu and Chen [14] developed V-doped TiO_2 with enhanced photocatalysis, while Li et al. [15] designed metal/N-doped carbon catalysts for nitrophenol reduction. Imoisili et al. [16] used microwave-assisted sol–gel for TiO_2-based photocatalysts, and Hassani Rad et al. [17] produced Ni/Al_2O_3 catalysts with promoters for methane reforming, showing high stability.

3.2. Hydrothermal synthesis

Hydrothermal synthesis allows formation of various nanostructures under controlled temperature and pressure in aqueous solutions, offering precise size and shape control, suitable for unstable or high vapor pressure materials [18].

3.3. Chemical vapor deposition (CVD)

Chemical Vapor Deposition deposits thin films or coatings via reactions of gases on heated substrates. It produces uniform, high-quality coatings, ideal for electronics, catalysis, and protective layers [19-24]. Advanced reactor designs (fluidized beds, spouted beds) improve material treatment and scale-up [25, 26]. Notably, researchers improved CNT growth by optimizing catalyst pretreatment temperatures [19], and ZIF-67 MOFs were successfully used as cost-effective catalysts for SWCNT production, replacing toxic and expensive precursors with environmentally friendly alternatives [20]. Additionally, plasma enhanced chemical vapor deposition (PECVD) offers a non-invasive way to deposit metal films on delicate nanostructures, enhancing antibacterial properties and photocatalytic activity at various speeds [27].

3.4. Biogenic synthesis

Nature, through plants, algae, fungi, and microorganisms, provides biomolecules that facilitate eco-friendly nanoparticle synthesis. Using waste materials reduces costs, minimizes hazardous chemicals, and promotes green methods. Computational studies help understand how biomolecules bind to nanoparticles, with applications in biomedicine, catalysis, and sensors [28].

Nanobiotechnology has become vital, with biological systems such as bacteria, fungi, and plants used to produce metal and metal oxide nanoparticles. Plant-based biosynthesis, especially extracellular, offers a quick, clean, and eco-friendly route, yet remains underexplored. Recent trends focus on synthesizing noble metal nanoparticles like silver, gold, platinum, and palladium via plants [29].

Nanoparticles, notably gold, are crucial in medicine (drug delivery for cancer, cardiovascular diseases, diabetes), environmental cleanup, and biosensors. Green synthesis methods, using plants or microbes, reduce toxic chemicals and enhance bioavailability. Eco-friendly nanotechnology is advancing, with research into iron, iron sulfides, and oxides for diverse uses [30].

Microorganisms, such as bacteria and fungi, aid in nanoparticle synthesis, offering advantages like specific shape control, but face challenges in scalability and precision. They can produce nanoparticles intra- or extracellularly through different pathways, such as enzyme-mediated reduction (e.g., bacteria reducing gold ions or fungi trapping silver ions). Developing eco-friendly, cost-effective synthesis methods is critical for environmental and biomedical applications [31, 32].

While physical and chemical methods exist, biological synthesis offers safer, controllable, and lower-toxicity alternatives. Parameters like pH, temperature, and biological source influence nanoparticle formation, and genetic manipulation of microbes can optimize production. Ensuring safety and understanding mechanisms are essential for translating biogenic nanomaterials into commercial and medical use, with regulations needed to manage potential toxicity [10].

3.5. Other emerging methods

Innovative synthesis techniques are rapidly advancing nanocatalyst development. For example, Flame Aerosol Synthesis (FAS) has been widely used in industry for mass-producing nanoparticles and has recently become a promising method for fabricating novel catalytic nanomaterials. Flame spray pyrolysis (FSP), a subset of FAS, enables the scalable and versatile creation of metal oxide and noble metal nanoparticles, which are now applied in areas like CO_2 utilization, gas sensing, and water splitting, beyond traditional catalysis [33].

Furthermore, composite nanocatalysts, assembled via methods such as sol-gel, impregnation, co-precipitation, hydrothermal synthesis, or auto-combustion, offer advantages like controlled morphology, high purity, and reproducibility. These composites outperform their single-component counterparts in sectors like energy, environmental remediation, pharmaceuticals, and petrochemicals. Optimizing synthesis techniques to enhance stability, efficiency, and application scope remains key, promising continued growth and innovation in the field of nanocatalysis [34]. Nanotechnology in catalysis spans both research and industry, where nanocatalysts are vital for environmental, social, and industrial applications. With many patents and commercial products emerging, advanced nanocatalysts now exhibit superior activity, selectivity, durability, and recoverability—making them essential tools for solving global challenges [35].

4. Types of nano catalysts

4.1. Heterogeneous nano catalysts

In homogeneous nanocatalysis, nanoparticles are suspended in a solution. To prevent aggregation, which reduces surface area and catalytic efficiency, they're often stabilized with polymers. However, this stabilization can lower catalytic activity and makes recovering nanoparticles challenging, raising environmental concerns since removed nanoparticles are hard to destroy and may accumulate in ecosystems [2, 8].

4.2. Homogeneous nano catalysts

Heterogeneous catalysis, where catalysts are in a different phase (often solids), is more environmentally friendly due to easier recovery. Recent research focuses on nanoparticles supported on materials like silica, carbon fibers, or clays, and on creating nanostructured surfaces with controlled features. Key scientific challenges include understanding how nanoparticle composition and structure influence activity and developing precise synthesis methods. Advances in nanotechnology are promising for future catalyst development [2, 8].

5. Applications of nano catalysis

Catalytic technologies are essential for advancing energy production, chemical manufacturing, and environmental protection, aiding in fuel generation, petrochemical synthesis, and emission reduction. They also play a crucial role in optimizing fuel cell electrodes. Nanocatalysis has a wide range of applications across multiple sectors, including environmental remediation, energy conversion and storage, pharmaceuticals, and sustainable fuel production such as biodiesel [5].

5.1. Environmental remediation

Growing population and industrial waste disturb ecological balance, making pollution remediation urgent. Some pollutants are tough to degrade, requiring advanced nanotechnology strategies. Nanomaterials' large surface area, active sites, and functional groups enable transformation of pollutants into harmless substances or their removal from water and environment. Nanomaterials e.g., organic, inorganic, and polymeric are effectively used to remove heavy metals, dyes, chlorinated organics, pesticides, volatile compounds, and herbicides. Methods like adsorption and photocatalytic reduction are prominent for reducing pollutant concentrations [36, 37]. Future work should focus on enhancing nanocatalyst efficiency to achieve safer, cleaner environments. Fig. 3 shows the schematic illustration of the process for removing metal ions using nanocatalysts.

Nanocatalysts, mainly metal nanoparticles and semiconductors, show high activity against bacteria, viruses, radioactive elements, and organic pollutants, offering promising solutions to water pollution. Common types include photocatalysts, Fenton-based, and antimicrobial catalysts. For example, Fe_2O_3 nanoparticles act as Fenton catalysts with H_2O_2 to degrade organic pollutants at room temperature without UV light. Combining Fe_2O_3 with materials like graphene or g-C_3N_4 enhances photocatalytic degradation under visible light [36].

Nanoparticles like TiO_2, Ag, ZnO, and magnetic nanoparticles are used in water and air purification, leveraging properties like hydroxyl radical production and antimicrobial activity. Surface modifications of materials like graphene oxide improve contaminant adsorption, making them highly effective in removing heavy metals, fluoride, and other toxins [36].

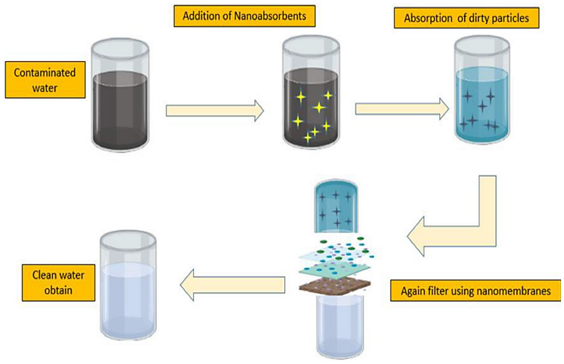

Fig. 3. Schematic illustration of the process for removing metal ions using nanocatalysts [36].

Nanomaterials in various forms (particles, fibers, tubes) excel as adsorbents and catalysts to eliminate gases, heavy metals, organic chemicals, and biological contaminants. Their high surface area gives them superior reactivity compared to conventional methods [38, 39]. Recent advances include using plant extracts to biosynthesize nanoparticles like ZnO for photocatalytic pollutant removal [40]. In addition, specialized nanocatalysts such as Pd on modified zeolite enable highly efficient pollutant reduction at ambient temperatures, with recyclability. Strong metal-support interactions (SMSIs) and oxide-support interactions (SOSIs), like embedded Pt or Ag nanoparticles on TiO_2, improve catalyst stability and activity under visible light, aiding pollutant oxidation at room temperature [41]. Nanocatalysts also play a key role in removing pesticides from soil and water, with particle size directly affecting adsorption capacity. They are effective in detecting and degrading environmental toxicants, offering a versatile and efficient approach for pollution control [42].

5.2. Energy conversion and storage

In recent decades, there has been growing focus on integrated energy systems that simultaneously convert and store various forms of energy, such as solar, mechanical, and thermal. These systems combine technologies like solar cells, thermoelectric generators, batteries, and supercapacitors. Advances in these areas promise practical, high-performance solutions for energy needs [43]. Nanostructured materials, with their large surface areas and unique physical properties, play a pivotal role in enhancing energy devices like solar cells, batteries, supercapacitors, and hydrogen storage. They improve performance by increasing reaction surfaces, boosting light absorption, and facilitating efficient ion and electron transport. Continued innovation in nanomaterials is expected to further advance energy technologies [44]. Fig. 4 displays major application areas of nanocatalysts across various industries [45]. Developments in nanomaterials such as nanoelectrolytes and nanoelectrodes are crucial for next-generation batteries, fuel cells, and supercapacitors, helping address global warming and resource limitations [46]. The surface properties of nanocrystals, like high-energy step and kink atoms, contribute to their catalytic efficiency, though synthesizing such structures remains challenging [47]. Key reactions like oxygen reduction, oxygen evolution, and hydrogen evolution are central to clean energy devices but face challenges due to slow reaction kinetics and reliance on costly noble metals. Developing efficient, stable, and cost-effective nanocatalysts for these reactions is a major goal for renewable energy commercialization [48].

Surface plasmons, collective electron oscillations, are increasingly used to enhance catalytic processes. Plasmonic nanocatalysis can improve reaction rates, selectivity, and stability, offering promising pathways for applications such as H_2 production, CO_2 reduction, and pollutant degradation, supporting sustainable catalysis progress [49].

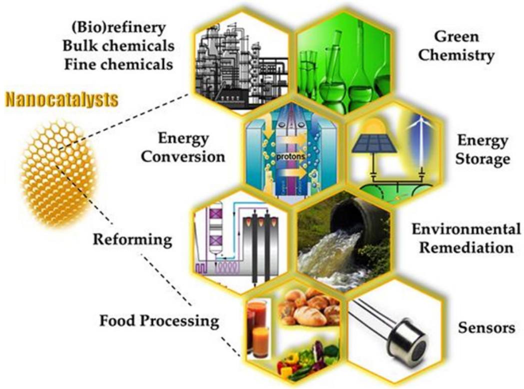

Fig. 4. Major application areas of nanocatalysts across various industries [45].

5.3. Pharmaceutical

Catalysis and medicine, traditionally seen as separate fields, are now converging thanks to advances in nanochemistry. A growing number of nanocatalysts such as nanozymes, photocatalysts, and electrocatalysts are used in vivo to trigger catalytic reactions and influence biological environments for therapeutic purposes. This emerging field, known as "nanocatalytic medicine," aims to combine the high efficiency and selectivity of traditional catalysis with targeted, minimal-side-effect therapies, advancing nanomedicine. Recent progress includes understanding how catalytic nanomaterials enable theranostic functions, promising to play a significant role in future medical treatments [50]. In recent years, magnetic nanocatalysts have been developed to aid complex organic syntheses, including pharmaceutical ingredient production. These biodegradable and biocompatible materials streamline processes, reduce purification steps, and utilize inexpensive raw materials, making them attractive for green chemistry applications. They are useful in synthesizing compounds like biphenyl and pyrrole derivatives [51]. Insights from industrial catalysis can inform nanocatalytic medicine, but the field is still limited. Comparing catalytic reactions in industry and medicine helps in designing appropriate catalysts for medical uses [52]. Finally, nanobiocatalysts i.e., combinations of enzymes and nanomaterials offer stable, reusable, and efficient biocatalytic platforms, overcoming challenges related to enzyme stability and recovery, and supporting sustainable bioprocessing methods [53].

5.4. Biodiesel production

Due to food shortages and rising fuel costs, researchers are exploring non-edible feedstocks for sustainable biodiesel production. Using waste oils and residues like animal fats helps avoid food competition and reduces costs. Various nanocatalysts, such as CaO, Li/ZnO–Fe_3O_4, and nano-sulfated zirconia, have shown high biodiesel yields (over 98%) and can replace traditional catalysts by eliminating washing steps and lowering production costs [54]. Nanocatalysts, especially magnetic ones, facilitate biodiesel synthesis through mild processes like transesterification and esterification, offering advantages like easy separation and recyclability [55]. They blend the benefits of homogeneous and heterogeneous catalysis, providing high activity with recyclability and environmental friendliness [56, 57]. Recent innovations in nanotechnology have significantly advanced biodiesel as a renewable, eco-friendly fuel, helping reduce dependence on fossil fuels [58]. The development of nanocatalysts with enhanced surface area, stability, and selectivity is crucial for large-scale biodiesel production. Optimizing these catalysts and process parameters can further boost efficiency, making biodiesel a promising alternative fuel to combat environmental issues and resource limitations [59].

6. Conclusion

As global challenges related to climate change, energy security, and environmental sustainability intensify, innovations in catalysis are becoming increasingly vital across energy, chemical synthesis, and environmental sectors. In recent years, advancements in nanotechnology have significantly influenced research on catalytic activities and the development of new, more efficient catalysts. The use of nanomaterials, especially inorganic nanoparticles, has attracted widespread scientific interest worldwide in designing innovative and environmentally friendly methods. These nanoparticles can act as catalysts or mediators, facilitating reactions in novel environments such as water. Due to their tiny size and large surface area, nano-catalysts have emerged as promising candidates to bridge the gap between homogeneous and heterogeneous catalysis, often resulting in faster reaction rates. Additionally, nanoparticles possess unique properties that provide extra functionalities to the reactants. Consequently, the pursuit of eco-friendly and cost and energy-effective catalysts has propelled nano-catalysis into a prominent field of study, with broad applications in both academic research and industrial processes.

Author contributions

Tahmineh Razipour: Investigation, Writing – original draft, Writing – review & editing; **Noushin Ezati:** Investigation, Writing – original draft, Writing – review & editing; **Ebadullah Asadi:** Investigation, Writing – review & editing, Supervision**; Mahnaz Dadkhah:** Conceptualization, Writing – original draft, Writing – review & editing.

Funding

No funding was received for this study.

Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

REFERENCES

[1] V. Polshettiwar, R.S. Varma, Green chemistry by nano-catalysis, Green Chemistry 12(5) (2010) 743-754.
[2] A. Chaudhary, A. Singh, Nano Catalysts: A Newfangled Gem in the Catalytic World, Recent Adv. Petrochemical Sci 3(5) (2017) 3-6.
[3] S.B. Somwanshi, S.B. Somvanshi, P.B. Kharat, Nanocatalyst: A brief review on synthesis to applications, Journal of Physics: Conference Series, IOP Publishing, 2020, p. 012046.
[4] S. Eskandarinezhad, R. Khosravi, M. Amarzadeh, P. Mondal, F.J.C. Magalhães Filho, Application of different Nanocatalysts in industrial effluent treatment: A review, Journal of Composites and Compounds 3(6) (2021) 43-56.

[5] S. Chaturvedi, P.N. Dave, N.K. Shah, Applications of nano-catalyst in new era, Journal of Saudi Chemical Society 16(3) (2012) 307-325.
[6] C. Costentin, J.-M. Savéant, Catalysis at the nanoscale may change selectivity, Proceedings of the National Academy of Sciences 113(42) (2016) 11756-11758.
[7] M. Pagliaro, R. Ciriminna, M. Yusuf, S. Eskandarinezhad, I.A. Wani, M. Ghahremani, Z.R. Nezhad, Application of nanocellulose composites in the environmental engineering as a catalyst, flocculants, and energy storages: A review, Journal of Composites and Compounds 3(7) (2021) 114-128.
[8] S.B. Singh, P.K. Tandon, Catalysis: a brief review on nano-catalyst, J. Energy Chem. Eng 2(3) (2014) 106-115.
[9] A.Z. Msezane, Z. Felfli, D. Sokolovski, Novel mechanism for nanoscale catalysis, Journal of Physics B: Atomic, Molecular and Optical Physics 43(20) (2010) 201001.
[10] A. Roy, A. Elzaki, V. Tirth, S. Kajoak, H. Osman, A. Algahtani, S. Islam, N.L. Faizo, M.U. Khandaker, M.N. Islam, Biological synthesis of nanocatalysts and their applications, Catalysts 11(12) (2021) 1494.
[11] D. Bokov, A. Turki Jalil, S. Chupradit, W. Suksatan, M. Javed Ansari, I.H. Shewael, G.H. Valiev, E. Kianfar, Nanomaterial by sol-gel method: synthesis and application, Advances in materials science and engineering 2021(1) (2021) 5102014.
[12] L. Bazli, M. Siavashi, A. Shiravi, A review of carbon nanotube/TiO2 composite prepared via sol-gel method, Journal of Composites and Compounds 1(1) (2019) 1-9.
[13] S.M. Sajjadi, M. Haghighi, F. Rahmani, Sol-gel synthesis and catalytic performance of Ni-Co/Al 2 O 3-MgO-ZrO 2 nanocatalyst with different ZrO 2-loadings used in CH 4/CO 2 reforming for hydrogen production, International Journal of Oil, Gas and Coal Technology 8(3) (2014) 304-324.
[14] J.C.-S. Wu, C.-H. Chen, A visible-light response vanadium-doped titania nanocatalyst by sol–gel method, Journal of Photochemistry and Photobiology A: Chemistry 163(3) (2004) 509-515.
[15] P. Li, H. Wang, S. Jiang, J. Wang, Z. Cao, J. Yang, Rational design of metal/N-doped carbon nanocatalysts via sol-gel method for obtaining high catalytic activity toward reduction reactions of 4-nitrophenol and Rhodamine B, Applied Catalysis A: General 631 (2022) 118479.
[16] P.E. Imoisili, T.-C. Jen, B. Safaei, Microwave-assisted sol–gel synthesis of TiO2-mixed metal oxide nanocatalyst for degradation of organic pollutant, Nanotechnology Reviews 10(1) (2021) 126-136.
[17] S.J.H. Rad, M. Haghighi, A.A. Eslami, F. Rahmani, N. Rahemi, Sol–gel vs. impregnation preparation of MgO and CeO2 doped Ni/Al2O3 nanocatalysts used in dry reforming of methane: Effect of process conditions, synthesis method and support composition, International Journal of Hydrogen Energy 41(11) (2016) 5335-5350.
[18] Q. Yang, Z. Lu, J. Liu, X. Lei, Z. Chang, L. Luo, X. Sun, Metal oxide and hydroxide nanoarrays: Hydrothermal synthesis and applications as supercapacitors and nanocatalysts, Progress in natural science: Materials International 23(4) (2013) 351-366.
[19] J. Lee, G.N. Tomaraei, M. Abdulhafez, M. Bedewy, Boosting catalytic lifetime in chemical vapor deposition of carbon nanotubes by rapid thermal pretreatment of alumina-supported metal nanocatalysts, Chemistry of Materials 33(16) (2021) 6277-6289.
[20] J. Luan, W.-L. Duan, Y.-X. Li, F.-B. Meng, Y. Liu, X.-S. Zhang, J. Zhou, W.-Z. Li, Y. Fu, Metal–organic framework as catalyst precursor of floating catalyst chemical vapor deposition for single-walled carbon nanotube manufacture, ACS Sustainable Chemistry & Engineering 11(33) (2023) 12423-12434.
[21] D.L. García-Ruiz, F.G. Granados-Martínez, C.J. Gutiérrez-García, J.M. Ambriz-Torres, J. de Jesús Contreras-Navarrete, N. Flores-Ramírez, F. Méndez, L. Domratcheva-Lvova, Synthesis of carbon nanomaterials by chemical vapor deposition method using green chemistry principles, Handbook of greener synthesis of nanomaterials and compounds, Elsevier2021, pp. 273-314.
[22] K.H. Habig, Chemical vapor deposition and physical vapor deposition coatings: properties, tribological behavior, and applications, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films 4(6) (1986) 2832-2843.
[23] J.-O. Carlsson, P.M. Martin, Chemical vapor deposition, Handbook of Deposition Technologies for films and coatings, Elsevier2010, pp. 314-363.
[24] Y. Xu, X.-T. Yan, Introduction to chemical vapour deposition, Chemical Vapour Deposition: An Integrated Engineering Design for Advanced Materials (2010) 1-28.
[25] C. Vahlas, B. Caussat, P. Serp, G.N. Angelopoulos, Principles and applications of CVD powder technology, Materials Science and Engineering: R: Reports 53(1-2) (2006) 1-72.
[26] J. Creighton, P. Ho, Introduction to chemical vapor deposition (CVD), ASM international 407 (2001).
[27] N. Subjalearndee, D. Hegemann, M. Amberg, B. Hanselmann, P. Rupper, V. Intasanta, Structural development of nanosilver on metal oxide nanofibrous membrane by plasma enhanced chemical vapor deposition (PECVD), Applied Surface Science 452 (2018) 306-313.
[28] D. Sharma, S. Kanchi, K. Bisetty, Biogenic synthesis of nanoparticles: a review, Arabian journal of chemistry 12(8) (2019) 3576-3600.
[29] M.S. Akhtar, J. Panwar, Y.-S. Yun, Biogenic synthesis of metallic nanoparticles by plant extracts, ACS Sustainable Chemistry & Engineering 1(6) (2013) 591-602.
[30] S. Menon, S. Rajeshkumar, V. Kumar, A review on biogenic synthesis of gold nanoparticles, characterization, and its applications, Resource-Efficient Technologies 3(4) (2017) 516-527.
[31] A.B. Seabra, P. Haddad, N. Duran, Biogenic synthesis of nanostructured iron compounds: applications and perspectives, IET nanobiotechnology 7(3) (2013) 90-99.
[32] B. Mughal, S.Z.J. Zaidi, X. Zhang, S.U. Hassan, Biogenic nanoparticles: Synthesis, characterisation and applications, Applied Sciences 11(6) (2021) 2598.
[33] Y. Sheng, M. Kraft, R. Xu, Emerging applications of nanocatalysts synthesized by flame aerosol processes, Current opinion in chemical engineering 20 (2018) 39-49.
[34] T. AbdulRasheed, B. Afotey, D.A. Anang, Recent Advances in Methods for Synthesizing Composite Nanocatalysts and Their Applications: A Literature Review, Int. J. Thin. Fil. Sci. Tec 13(1) (2023) 27-36.
[35] S. Olveira, S.P. Forster, S. Seeger, Nanocatalysis: academic discipline and industrial realities, Journal of Nanotechnology 2014(1) (2014) 324089.
[36] R. Ningthoujam, Y.D. Singh, P.J. Babu, A. Tirkey, S. Pradhan, M. Sarma, Nanocatalyst in remediating environmental pollutants, Chemical Physics Impact 4 (2022) 100064.
[37] S. Bahadori, M. Azimpour, Advancements in Nanoparticle-Supported Laccase Immobilization: Promising Solutions for Water Treatment, Journal of Composites and Compounds 5(16) (2023) 159-178.
[38] M.M. Khin, A.S. Nair, V.J. Babu, R. Murugan, S. Ramakrishna, A review on nanomaterials for environmental remediation, Energy & Environmental Science 5(8) (2012) 8075-8109.
[39] P. Salahshour, M. Yavari, F. Güleç, H. Karaca, S. Tarighi, S. Habibzadeh, Development of heavy metal passivators in residue fluid catalytic cracking process, Journal of Composites and Compounds 4(13) (2022).
[40] O.A. Zelekew, H.H. Haitosa, X. Chen, Y.-N. Wu, Recent progress on plant extract-mediated biosynthesis of ZnO-based nanocatalysts for environmental remediation: Challenges and future outlooks, Advances in Colloid and Interface Science 317 (2023) 102931.
[41] K. Fujiwara, K. Okuyama, S.E. Pratsinis, Metal–support interactions in catalysts for environmental remediation, Environmental Science: Nano 4(11) (2017) 2076-2092.
[42] S. Singh, V. Kumar, S. Datta, D. Bhatia, V. Dhaka, J. Singh, Novel strategies for environmental remediation of pesticides using nanocatalysts, Biobased Nanotechnology for Green Applications (2021) 543-556.
[43] B. Luo, D. Ye, L. Wang, Recent progress on integrated energy conversion and storage systems, Advanced Science 4(9) (2017) 1700104.
[44] Q. Zhang, E. Uchaker, S.L. Candelaria, G. Cao, Nanomaterials for energy conversion and storage, Chemical Society Reviews 42(7) (2013) 3127-3171.
[45] P. Prinsen, R. Luque, Introduction to nanocatalysts, (2019).
[46] A.S. Arico, P. Bruce, B. Scrosati, J.-M. Tarascon, W. Van Schalkwijk, Nanostructured materials for advanced energy conversion and storage devices, Nature materials 4(5) (2005) 366-377.
[47] Z.-Y. Zhou, N. Tian, J.-T. Li, I. Broadwell, S.-G. Sun, Nanomaterials of high surface energy with exceptional properties in catalysis and energy storage, Chemical Society Reviews 40(7) (2011) 4167-4185.
[48] S. Ghosh, R.N. Basu, Multifunctional nanostructured electrocatalysts for energy conversion and storage: current status and perspectives, Nanoscale 10(24) (2018) 11241-11280.
[49] M. Dhiman, Plasmonic nanocatalysis for solar energy harvesting and sustainable chemistry, Journal of Materials Chemistry A 8(20) (2020) 10074-10095.
[50] B. Yang, Y. Chen, J. Shi, Nanocatalytic medicine, Advanced materials 31(39) (2019) 1901778.
[51] R. Taheri-Ledari, A. Maleki, Magnetic nanocatalysts utilized in the synthesis of aromatic pharmaceutical ingredients, New Journal of Chemistry 45(9) (2021) 4135-4146.
[52] Z. Jin, L. Jiang, Q. He, Critical learning from industrial catalysis for nanocatalytic medicine, Nature Communications 15(1) (2024) 3857.
[53] D.S. Khafaga, M.G. Radwan, G. Muteeb, M. Aatif, M. Farhan, Green synthesis of biocatalysts based on nanocarriers promises an effective role in pharmaceutical and biomedical fields, Catalysts 13(11) (2023) 1448.
[54] Y. Zhang, L. Duan, H. Esmaeili, A review on biodiesel production using various heterogeneous nanocatalysts: Operation mechanisms and performances, Biomass and Bioenergy 158 (2022) 106356.
[55] S.A. Hosseini, Nanocatalysts for biodiesel production, Arabian Journal of Chemistry 15(10) (2022) 104152.
[56] A. Zuliani, F. Ivars, R. Luque, Advances in nanocatalyst design for biofuel production, ChemCatChem 10(9) (2018) 1968-1981.
[57] S. Bano, A.S. Ganie, S. Sultana, S. Sabir, M.Z. Khan, Fabrication and optimization of nanocatalyst for biodiesel production: an overview, Frontiers in Energy Research 8 (2020) 579014.
[58] M. Narasimhan, M. Chandrasekaran, S. Govindasamy, A. Aravamudhan, Heterogeneous nanocatalysts for sustainable biodiesel production: A review, Journal of Environmental Chemical Engineering 9(1) (2021) 104876.
[59] A.P. Ingle, A.K. Chandel, R. Philippini, S.E. Martiniano, S.S. da Silva, Advances in nanocatalysts mediated biodiesel production: a critical appraisal, Symmetry 12(2) (2020) 256.