STM JOURNALS

Journal of
Catalyst & Catalysis

ISSN: 2349-4344
Volume 13, Issue 2, 2026
May–August
DOI (Journal): 10.37591/JoCC

http://engineeringjournals.stmjournals.in/index.php/JoCC/index

Review JoCC

# Modern Catalytic Systems: Mechanisms, Materials Engineering, and Sustainable Applications

Bijoy Kumar Mondal[1,*]

***Abstract***

*Catalysis is a fundamental pillar of modern chemical science and industrial manufacturing, enabling efficient production of fuels, chemicals, pharmaceuticals, polymers, and environmentally important products through the acceleration of chemical reactions and reduction of activation energy barriers. This review provides a comprehensive overview of contemporary catalytic systems, with emphasis on the relationship between catalyst structure, reaction mechanisms, catalytic performance, and long-term stability. The discussion begins with the classification of homogeneous, heterogeneous, fluorous biphasic, polymer-supported, and nanostructured catalytic systems, highlighting their mechanistic features, advantages, limitations, and industrial relevance. Particular attention is given to zeolite-based catalysts, porous materials, and nanoscale engineering strategies that improve surface reactivity, selectivity, and resistance to deactivation. Recent developments in nanocatalysts, single-atom catalysts, and hybrid catalytic platforms are examined in relation to sustainable chemical transformations, including hydrogen production, biomass valorization, carbon dioxide reduction, and photocatalytic processes. The review also analyzes major catalyst deactivation pathways, including poisoning, coke deposition, sintering, leaching, and structural degradation, together with current regeneration and stabilization strategies. Emerging trends such as photothermal catalysis, biomimetic catalytic systems, and renewable-energy-driven catalytic cycles are further discussed as future directions for sustainable chemical manufacturing. Overall, this review highlights how advances in catalyst design, mechanistic understanding, and materials engineering continue to shape the development of greener, more efficient, and economically viable catalytic technologies for modern industrial applications.*

**Keywords:** Homogeneous catalysis, heterogeneous catalysis, nanocatalysts, sustainable catalysis, catalyst deactivation, catalyst engineering

## INTRODUCTION

Catalysis represents one of the foundational technologies in modern chemical science and industrial manufacturing [1]. By lowering activation energy barriers and increasing reaction rates, catalysts enable the efficient production of fuels, chemicals, pharmaceuticals, fertilizers, polymers, and countless other industrial products. It is estimated that more than 80% of all industrial chemical processes involve at least one catalytic step, underscoring the enormous economic and technological significance of catalytic systems [2]. Beyond improving reaction efficiency, catalysis also contributes to enhanced product selectivity, reduced waste generation, and lower overall energy consumption, making it central to sustainable chemical development.

*Author for Correspondence
Bijoy Kumar Mondal
E-mail: bijoykumarmondal05@uhsc.edu.bd

Assistant professor, Department of Chemistry, Uttara High School and College, Dhaka, Bangladesh

Received Date: May 29, 2026
Accepted Date: June 03, 2026
Published Date: June 25, 2026

**Citation:** Bijoy Kumar Mondal. Modern Catalytic Systems: Mechanisms, Materials Engineering, and Sustainable Applications. Journal of Catalyst & Catalysis. 2026; 13(2): 1–8p.

Traditional catalytic systems, including homogeneous and heterogeneous catalysts, have played a dominant role in industrial chemistry for decades. Homogeneous catalysts often exhibit excellent activity and selectivity due to uniform active sites and molecular-level control; however, they suffer from challenges related to catalyst

 

recovery, separation, and recyclability [3]. In contrast, heterogeneous catalysts offer easier separation and greater operational stability but may experience lower selectivity and mass-transfer limitations. Furthermore, many conventional catalysts are susceptible to catalyst poisoning, sintering, leaching, and thermal degradation under harsh reaction environments, which can significantly reduce catalytic lifetime and industrial efficiency [4].

Growing environmental concerns and stricter sustainability regulations have accelerated the search for greener and more efficient catalytic technologies. Green catalysis focuses on minimizing hazardous waste, reducing energy requirements, and enabling environmentally benign reaction pathways [5]. Among the emerging approaches, fluorous biphasic catalysis has attracted attention due to its ability to combine the high activity of homogeneous catalysts with improved catalyst recovery through phase separation techniques [6]. Similarly, polymer-supported catalysts provide enhanced recyclability and operational convenience by immobilizing active catalytic species onto solid polymer matrices. Zeolite-based catalysts and structured porous materials have also become highly important because of their tunable pore architectures, shape selectivity, thermal stability, and strong acidity, which make them highly effective in petrochemical refining and selective organic transformations [7, 8].

Recent advances in nanotechnology have further transformed the field of catalysis by enabling precise engineering of catalytic surfaces at the atomic and molecular scales. Nanostructured catalysts possess exceptionally high surface-area-to-volume ratios, leading to increased exposure of active sites and improved catalytic efficiency [9, 10]. In addition, nanoscale control allows modulation of electronic, geometric, and surface properties, thereby enhancing catalytic activity, selectivity, and resistance to deactivation. Metal nanoparticles, bimetallic systems, core–shell nanostructures, and supported nanocatalysts have demonstrated remarkable performance across a wide range of industrial and environmental applications, including hydrogen production, carbon dioxide reduction, fuel-cell technologies, and biomass conversion [11, 12].

Despite these advances, catalyst deactivation remains a major challenge limiting long-term industrial performance. Mechanisms such as coke deposition, poisoning by impurities, active-site restructuring, thermal sintering, and support degradation can significantly affect catalyst stability and process economics [13, 14]. Therefore, understanding the relationship between catalyst structure, reaction mechanism, and deactivation behavior is essential for the rational design of durable and high-performance catalytic systems.

This review provides a mechanistic and material-oriented overview of modern catalytic technologies, highlighting the interplay between catalyst composition, surface structure, and catalytic performance. Particular emphasis is placed on green catalytic systems, nanostructured catalysts, and advanced porous materials, with discussion of their synthesis strategies, functional properties, stability, and industrial relevance. In addition, the review examines major deactivation pathways and current approaches aimed at improving catalyst lifetime, recyclability, and sustainability in modern chemical processes.

## CLASSIFICATION OF CATALYTIC SYSTEMS

### Homogeneous Catalysis

Homogeneous catalysis involves catalysts and reactants existing within the same phase, most commonly in liquid solution. These catalytic systems are widely valued for their exceptional activity, high selectivity, and precise molecular-level control over reaction pathways. Because the catalytic species are uniformly dispersed throughout the reaction medium, homogeneous catalysts provide well-defined active sites that facilitate efficient interaction with substrates and allow detailed mechanistic understanding. Transition-metal complexes based on palladium, nickel, copper, rhodium, and ruthenium have become central to modern synthetic chemistry, particularly in carbon–carbon and carbon–heteroatom bond-forming reactions [15].

 

Among the most significant applications of homogeneous catalysis are cross-coupling reactions such as Suzuki, Heck, Sonogashira, and Negishi couplings, which are extensively employed in pharmaceutical synthesis, agrochemical production, and fine chemical manufacturing [16]. In addition, homogeneous catalytic systems are highly important in asymmetric synthesis, where chiral ligands create stereochemically controlled environments that favor the formation of one enantiomer over another. Ligand frameworks such as phosphoramidites, BINAP derivatives, and chiral N-heterocyclic carbenes have demonstrated remarkable efficiency in enantioselective conjugate additions, hydrogenation reactions, and cyclization processes [17, 18]. These ligand systems influence the electronic and steric environment around the metal center, thereby controlling reaction kinetics and stereochemical outcomes.

Despite their many advantages, homogeneous catalysts face several practical limitations that hinder large-scale industrial implementation. Separation of catalyst residues from reaction products is often difficult and costly, especially when expensive noble metals are involved [19]. Catalyst recovery and recycling are also challenging because the catalyst remains dissolved in the reaction mixture. Furthermore, many homogeneous catalysts exhibit limited thermal stability and may undergo ligand degradation or metal leaching under harsh operating conditions [20]. These drawbacks have motivated extensive research into immobilized and hybrid catalytic systems that aim to combine the selectivity of homogeneous catalysis with the operational advantages of heterogeneous processes.

**Heterogeneous Catalysis**

Heterogeneous catalysis involves catalysts existing in a different phase from the reactants, typically solid catalysts interacting with gaseous or liquid substrates. Owing to their ease of separation, mechanical robustness, and compatibility with continuous industrial processing, heterogeneous catalysts dominate large-scale chemical manufacturing and environmental remediation technologies. Reactions occur at the catalyst surface, where adsorption, surface diffusion, reaction, and desorption collectively determine catalytic performance [21, 22].

Zeolites represent one of the most important classes of heterogeneous catalysts because of their highly ordered microporous structures, tunable acidity, and remarkable thermal stability. Frameworks such as AFX, erionite, ZSM-5, and faujasite provide shape-selective catalytic environments capable of discriminating between molecules based on size and geometry [23]. This shape selectivity is particularly valuable in hydrocarbon cracking, isomerization, methanol-to-olefin conversion, and selective catalytic reduction of nitrogen oxides (NOx). The catalytic behavior of zeolites strongly depends on factors such as pore architecture, Si/Al ratio, acid-site density, and framework topology, all of which influence reactant accessibility and product distribution [24].

Metal-supported heterogeneous catalysts also play major roles in hydrogenation, oxidation, reforming, and environmental catalysis. [25] However, heterogeneous catalysts are not free from limitations. Catalyst deactivation caused by coking, poisoning, sintering, and structural collapse can significantly reduce activity over time. In addition, achieving the same degree of selectivity observed in homogeneous systems remains challenging because heterogeneous catalysts often possess heterogeneous distributions of active sites [26].

**Fluorous Biphasic Systems**

Fluorous biphasic catalysis has emerged as an innovative strategy for improving catalyst recovery while maintaining many advantages associated with homogeneous catalysis. In these systems, catalysts are modified with fluorinated “fluorous tags” that render them soluble in highly fluorinated solvents but poorly soluble in conventional organic phases [27]. During the reaction, substrates and products predominantly remain in the organic phase, while the catalyst partitions into the fluorous phase, enabling efficient separation after reaction completion [28].

 

This biphasic approach combines the high activity and selectivity characteristic of homogeneous catalysis with simplified catalyst recycling and reduced metal contamination of products. Fluorous biphasic systems have been successfully applied in hydroformylation, hydrogenation, oxidation, and carbon–carbon coupling reactions [29]. The fluorous phase can often be reused multiple times with minimal catalyst loss, thereby improving process sustainability and economic efficiency.

The effectiveness of fluorous catalysis depends strongly on the design of the fluorinated ligand, solvent compatibility, and partition coefficients between phases. Although fluorous systems offer important advantages in catalyst recovery, challenges remain regarding the high cost of fluorinated compounds, environmental concerns related to persistent fluorinated materials, and the need for specialized reaction media [30]. Nevertheless, fluorous biphasic catalysis continues to attract attention as a promising platform for greener and more recyclable catalytic technologies.

## CATALYST DESIGN AND ENGINEERING STRATEGIES

### Polymer-Supported Catalysts

Polymer-supported reagents and scavengers (PS-RCS approach) improve catalyst recovery and reduce metal contamination. These systems are widely applied in green organic synthesis and pharmaceutical manufacturing [31].

### Nanostructured Catalysts

Nanocatalysts exhibit high surface-to-volume ratios and tunable electronic properties. $CuO/CeO_2$ nanorods show excellent oxygen storage and redox behavior, enhancing oxidation reactions. Nano-zero-valent iron (nZVI) is widely used in environmental remediation and reductive degradation of pollutants [32].

### Zeolite Engineering

Zeolite synthesis using organic structure-directing agents (OSDAs) allows controlled pore formation. This enables selective catalysis in petrochemical cracking, NOx reduction, and hydrocarbon conversion [33].

### Mechanistic Pathways in Catalysis

Catalytic mechanisms depend strongly on system type. In homogeneous catalysis, ligand coordination and electron transfer govern reactivity. In asymmetric catalysis, chiral ligands induce enantioselectivity by stabilizing specific transition states.

In heterogeneous catalysis, adsorption and surface activation are key steps. Reactant molecules bind to active sites, followed by bond cleavage and product formation. Mechanisms such as nucleophilic attack, hydrogen abstraction, and electron transfer dominate many industrial reactions [34].

Photothermal catalysis represents a hybrid mechanism where light absorption generates localized heat, enhancing reaction rates under mild conditions. This is particularly important in $CO_2$ reduction and biomass conversion.

### Catalyst Deactivation Mechanisms

Catalyst deactivation is a critical challenge in industrial catalysis. Common causes include:

- Poisoning by sulfur or nitrogen compounds
- Coke formation blocking active sites
- Sintering of nanoparticles at high temperature
- Leaching of active metal species

In biological systems, catalytic inhibition can also be observed. For example, enzyme inhibition in DNA replication pathways or protein phosphatase disruption demonstrates how catalytic cycles can be blocked by inhibitors.

 

Understanding these mechanisms is essential for improving catalyst lifetime and developing regeneration strategies as shown in fig. 1.

**Sustainable Catalysis Applications**

Sustainable catalysis focuses on environmentally friendly processes. Biomass valorization converts lignocellulosic feedstocks into fuels and chemicals. Formic acid is a promising hydrogen carrier due to its ability to release hydrogen under catalytic decomposition as shown in table 1.

$CO_2$ reduction using nano-catalysts offers a pathway for carbon recycling. Photocatalytic systems driven by solar energy provide clean and renewable routes for chemical synthesis [35].

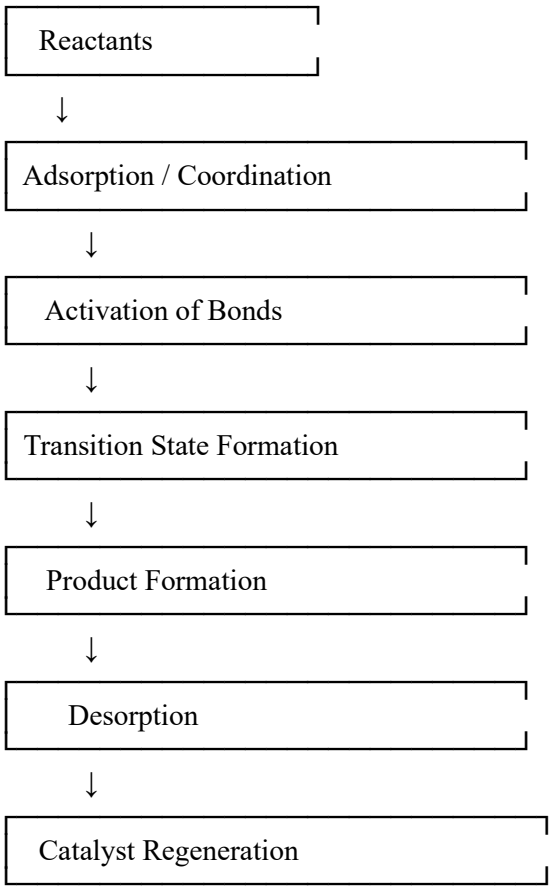


**Figure 1.** Catalytic reaction cycle (general mechanism).

**Table 1.** Comparison of catalytic systems.

| Catalyst Type | Advantages | Limitations | Applications |
|---|---|---|---|
| Homogeneous | High selectivity | Difficult separation | Fine chemicals, pharma |
| Heterogeneous | Reusable, stable | Diffusion limitations | Petrochemicals |
| Zeolites | Shape selectivity | Limited pore flexibility | NOx abatement |
| Polymer-supported | Easy recovery | Lower activity | Green synthesis |
| Nanocatalysts | High activity | Aggregation risk | Environmental catalysis |
| Fluorous systems | Easy separation | Costly materials | Specialty synthesis |

 

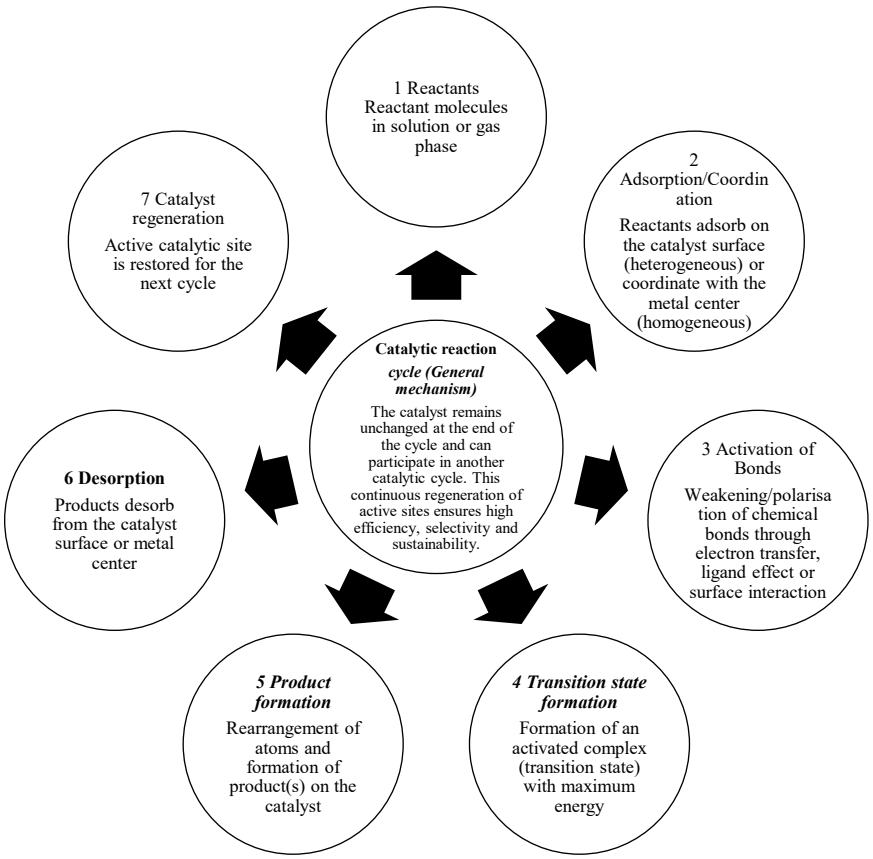


**Figure 2.** General catalytic cycle in heterogeneous and homogeneous systems.

This cycle in fig. 2 highlights the continuous regeneration of catalytic sites, which is fundamental to catalytic efficiency.

## Emerging Trends

Recent trends in catalysis include:

- Photothermal catalytic systems integrating light and heat activation
- Artificial enzyme-like catalysts with biomimetic selectivity
- AI-assisted catalyst design for predictive optimization
- Carbon-neutral catalytic cycles using renewable hydrogen sources
- Single-atom catalysts with maximum atom efficiency

These approaches represent the future direction of sustainable chemical synthesis.

## CONCLUSION

Catalysis continues to play a central role in the advancement of modern chemical science and industrial technology. Over the past decades, catalyst design has evolved significantly from traditional homogeneous and heterogeneous systems toward more sophisticated nanostructured, polymer-supported, fluorous, and environmentally sustainable catalytic platforms. These developments have enabled substantial improvements in reaction efficiency, selectivity, catalyst stability, and process sustainability, thereby addressing many of the limitations associated with conventional catalytic methods.

A deeper mechanistic understanding of catalytic reactions has become essential for the rational design of high-performance catalysts. The relationship between catalyst structure, electronic properties, surface chemistry, and reaction pathways directly determines catalytic activity and selectivity. At the same time,

 

understanding catalyst deactivation mechanisms—including poisoning, sintering, coke formation, leaching, and structural degradation—has provided valuable insights for improving catalyst durability and recyclability in industrial applications. Advances in characterization techniques, computational modeling, and surface science have further accelerated the development of catalysts with precisely engineered active sites and optimized functionalities.

Nanotechnology and materials engineering have introduced new possibilities for tailoring catalytic surfaces at atomic and molecular scales. Nanocatalysts, porous materials, and hybrid catalytic systems now offer enhanced surface-area-to-volume ratios, tunable electronic properties, and improved resistance to deactivation. Similarly, polymer-supported and fluorous biphasic systems have contributed to greener catalytic processes by facilitating catalyst recovery and reducing waste generation. These innovations align closely with the principles of green chemistry and the growing global demand for sustainable industrial practices.

Looking ahead, future research in catalysis is expected to focus on the development of multifunctional and highly selective catalytic systems capable of operating under mild and energy-efficient conditions. The integration of catalysis with renewable energy technologies, biomass conversion, hydrogen production, and carbon dioxide utilization will likely become increasingly important in achieving sustainable chemical manufacturing. In addition, environmentally benign catalytic cycles, recyclable catalyst architectures, and earth-abundant metal catalysts are anticipated to replace more hazardous and resource-intensive systems.

Overall, modern catalytic science represents a rapidly evolving interdisciplinary field that combines chemistry, materials science, nanotechnology, and engineering. Continued innovation in catalyst design and mechanistic understanding will remain crucial for addressing future challenges in energy, environment, and industrial production while supporting the transition toward greener and more sustainable chemical technologies.

**REFERENCES**

1. Anekwe IMS, Akpasi SO, Enemuo EM, Ashiegbu D, Mustapha SI, Isa YM. Innovations in catalytic understanding: a journey through advanced characterization. Mater Today Catal. 2024;7:100061.
2. Anekwe IMS, Akpasi SO, Tetteh EK, Joel AS, Mustapha SI, Isa YM. Progress in heterogeneous catalysis for renewable energy and petrochemical production from biomass. Fuel Process Technol. 2025;276:108267.
3. Xiao H, Goundry WRF, Griffiths R, Feng Y, Karlsson S. Recovery and reuse of homogeneous palladium catalysts via organic solvent nanofiltration: application in the synthesis of AZD4625. Green Chem. 2025;27(12):3186-3196.
4. Anekwe IMS, Isa YM. Unlocking catalytic longevity: a critical review of catalyst deactivation pathways and regeneration technologies. Energy Adv. 2025;4(5):1075-1113.
5. Kate A, Sahu LK, Pandey J, Mishra M, Sharma PK. Green catalysis for chemical transformation: the need for sustainable development. Curr Res Green Sustain Chem. 2022;5:100248.
6. Quintavalla A, Carboni D, Lombardo M. Recent advances in asymmetric synthesis of pyrrolidine-based organocatalysts and their application: a 15-year update. Molecules. 2023;28(5):2234.
7. Mondal BK, Islam MN, Hossain ME, Abser MN. Microstructural and mineralogical properties of acid and alkali activated coal fly ash. J Adv Chem Sci. 2019;5(4):612-614.
8. Serrano DP, Centi G, Diddams PA, Čejka J. Outlooks for zeolite catalysts in a low-carbon scenario. Catal Today. 2024;426:114365.
9. Mondal BK, Guha F, Abser MN. Sol-gel derived Ti-doped mesoporous silica-alumina: an efficient catalyst to recover energy sources from environmental hazard waste plastics. J Therm Anal Calorim. 2023;148(11):5257-5270.
10. Mondal BK, Guha F, Abser MN. Waste plastics-to-fuel using fly ash catalyst. Waste Dispos Sustain Energy. 2021;3(1):13-19.
11. Serna-Gallén P, Mužina K. Metallic nanoparticles at the forefront of research: novel trends in

 

catalysis and plasmonics. Nano Mater Sci. 2026;8(4):534-555.
12. Rahman M, Mondal BK, Ahmed N, Hossain MD. Catalytic pyrolysis of waste high-density (HDPE) and low-density polyethylene (LDPE) to produce liquid hydrocarbon using silica-alumina catalyst. J Bangladesh Acad Sci. 2023;47(2):195-203.
13. Rahman M, Roy SC, Hassan MM, Mondal BK, Faruk MO, Rahman MA, Zahiduzzaman M, Sharmin A, Hosen MJ, Afroze M, Khan M, Nasreen Z, Matin MA. Catalytic pyrolysis of waste plastics into liquid hydrocarbon using mesoporous kaolin clay. J Bangladesh Acad Sci. 2020;44(1):1-12.
14. Deng J, Hu X, Klaver AJ, Liu J, Liu B, Bai L, Xie M, Zhang D. Catalyst deactivation in the abatement of atmospheric pollutants: origin, resistance, and regeneration. Chem Rev. 2025;125(19):11260-11357.
15. Beletskaya IP, Ananikov VP. Transition-metal-catalyzed C-S, C-Se, and C-Te bond formations via cross-coupling and atom-economic addition reactions: achievements and challenges. Chem Rev. 2022;122(20):16110-16293.
16. Mohammadi L, Vaezi MR. Palladium nanoparticle-decorated porous metal-organic-framework (Zr)@guanidine: novel efficient catalyst in cross-coupling (Suzuki, Heck, and Sonogashira) reactions and carbonylative Sonogashira under mild conditions. ACS Omega. 2023;8(18):16395-16410.
17. Shen D, Xu Y, Shi SL. A bulky chiral N-heterocyclic carbene palladium catalyst enables highly enantioselective Suzuki-Miyaura cross-coupling reactions for the synthesis of biaryl atropisomers. J Am Chem Soc. 2019;141(38):14938-14945.
18. Ince S, Öner Ö, Yılmaz MK, Keleş M, Güzel B. Highly enantioselective binaphthyl-based chiral phosphoramidite stabilized-palladium nanoparticles for asymmetric Suzuki C-C coupling reactions. Inorg Chem. 2023;62(12):4637-4647.
19. Muthudineshkumar R, Anand R. Anaerobic digestion of various feedstocks for second-generation biofuel production. In: Advances in Eco-Fuels for a Sustainable Environment. Amsterdam: Elsevier; 2019. p. 157-185.
20. Xiao H, Goundry WRF, Griffiths R, Feng Y, Karlsson S. Recovery and reuse of homogeneous palladium catalysts via organic solvent nanofiltration: application in the synthesis of AZD4625. Green Chem. 2025;27(12):3186-3196.
21. Zhu ZS, Zhong S, Cheng C, Zhou H, Sun H, Duan X, Wang S. Microenvironment engineering of heterogeneous catalysts for liquid-phase environmental catalysis. Chem Rev. 2024;124(20):11348-11434.
22. Králik M, Kooš P, Markovič M, Lopatka P. Research and developments of heterogeneous catalytic technologies. Molecules. 2025;30(14):3279.
23. Nakamura T, Fedorov DG. The catalytic activity and adsorption in Faujasite and ZSM-5 zeolites: the role of differential stabilization and charge delocalization. Phys Chem Chem Phys. 2022;24(13):7739-7747.
24. Shvets OV, Kurmach MM, Mazur M, Golis P, Yaremov PS, Petrov O, Shcherban ND, Čejka J, Shamzhy MV. Topology-acidity-catalytic activity interplay in hierarchical nanolayered aluminosilicate zeolites for Friedel-Crafts alkylation. Catal Today. 2026;463:115580.
25. Reddy BM, Lakshmanan P, Bharali P, Saikia P, Thrimurthulu G, Muhler M, Grünert W. Influence of alumina, silica, and titania supports on the structure and CO oxidation activity of CexZr1-xO2 nanocomposite oxides. J Phys Chem C. 2007;111(28):10478-10483.
26. Anekwe IMS, Isa YM. Unlocking catalytic longevity: a critical review of catalyst deactivation pathways and regeneration technologies. Energy Adv. 2025;4(5):1075-1113.
27. Chandra G, Mahto B, Singh VR, Mahato GK, Rani U. Fluorescent fluorinated materials: a novel material for application in photodynamic therapy and designing chemical sensors. J Photochem Photobiol C Photochem Rev. 2024;60-61:100677.
28. Gottler LM, de la Salud-Bea R, Marsh ENG. The fluorous effect in proteins: properties of α4F6, a 4-α-helix bundle protein with a fluorocarbon core. Biochemistry. 2008;47(15):4484-4490.
29. Kokkinos NC. Modeling and simulation of biphasic catalytic hydrogenation of a hydroformylated

 

fuel. Int J Hydrogen Energy. 2021;46(39):19731-19736.
30. Han J, Kiss L, Mei H, Remete AM, Ponikvar-Svet M, Sedgwick DM, Roman R, Fustero S, Moriwaki H, Soloshonok VA. Chemical aspects of human and environmental overload with fluorine. Chem Rev. 2021;121(8):4678-4742.
31. Howard IC, Hammond C, Buchard A. Polymer-supported metal catalysts for the heterogeneous polymerisation of lactones. Polym Chem. 2019;10(43):5894-5904.
32. Dikshit PK, Kim BS, editors. Recent Advances on Nano-Catalysts for Biological Processes. Basel: MDPI; 2024.
33. Guha F, Abser MN, Mondal BK. Fate of waste plastics: a review. Next Res. 2025;2:100338.
34. Bañares MA, Daturi M. Understanding catalysts by time-/space-resolved operando methodologies. Catal Today. 2023;423:114255.
35. Guha F, Abser MN, Mandal BH, Mondal BK. Recent advancements in carbon capture, utilization, and sequestration technologies. Sustain Chem One World. 2025;7:100075.

 