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IMPORTANCE OF NANOPARTICLES AS CATALYSTS

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Abstract

Nanoparticles have grasped substantial attention as catalysts due to their distinctive size-dependent features, substantial surface area, and high catalytic activity. In recent years, they have emerged as vital tools in various chemical and industrial processes, offering several advantages over conventional catalysts. This comprehensive review highlights the importance of nanoparticles as catalysts, discussing their synthesis methods, applications, and the underlying mechanisms governing their catalytic performance. The role of different nanoparticle materials, such as metal, metal oxide, and carbon-based nanoparticles, is explored, along with their potential impact on sustainable and green chemistry. The review also addresses challenges and future prospects in the field of nanoparticle catalysis.

Keywords: Nanoparticles, Catalyst, Synthesis, Applications

1. Introduction

Many industrial and environmental processes rely on catalysis, which makes chemical reactions more efficient and environmentally friendly. Traditional catalysts frequently have drawbacks such as poor selectivity, low efficiency, and high cost. Nanoparticles have completely changed the field of catalysis and are consistently outperforming traditional catalysts having their high surface area to volume ratio and customizable characteristics. Materials having diameters typically between 1 and 100 nanometers are known as nanoparticles. They are incredibly well suited for catalytic applications because of their special size-dependent characteristics. Traditional bulk catalysts have a small surface area, which results in a smaller number of reaction-active sites. Contrarily, nanoparticles have a huge surface-to-volume ratio, offering a lot of active sites for catalysis and greatly increasing the process overall effectiveness. This in-depth review examines the amazing catalytic characteristics of nanoparticles and considers their significance in the field of contemporary chemistry and industry. The benefits of employing nanoparticles over traditional catalysts and the numerous methods by which they facilitate

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and enhance catalytic reactions will be the primary points of attention (Chaturvedi et al., 2012; Narayan et al., 2019; Astruc, 2020).

1.1 Nanoparticles and Catalysis: Catalysis is a fundamental process in chemistry that accelerates the rate of chemical reactions without being consumed in the process. It plays a crucial role in various industries, including petroleum refining, pharmaceuticals, environmental protection, and energy production. Traditional catalysts are often in the form of bulk materials with a large surface area, but in recent years, the use of nanoparticles as catalysts has gained significant attention due to their unique properties and enhanced catalytic efficiency. Ultra-small particles known as nanoparticles typically have a size between 1 and 100 nanometers. In comparison to bulk materials, nanoparticles have a much larger surface area per unit mass due to their smaller size. With more active sites for chemical reactions due to the greater surface area, they are more effective catalysts. The catalytic activity of these materials may also be further influenced by their size-dependent electrical and structural characteristics (Xia et al., 2013; Zhou et al., 2018; Gao and Yin, 2020).

1.2 Enhanced Catalytic Activity: High surface area-to-volume ratios in nanoparticle catalysts make it possible to expose more active areas. Due to the increased surface area compared to bulk materials, nanoparticle catalysts are more effective at speeding up chemical reactions. The creation of more potent catalysts for industrial processes may be facilitated by an understanding of the mechanisms that control this enhanced activity (Gupta et al., 2020; Kushwah et al., 2019; Yamada et al., 2020).

1.3 Tailoring Selectivity:

Nanoparticle catalysts have unique size, shape, and surface characteristics,
and show distinct selectivity for particular chemical pathways. This property of catalysts encourage the generation of desired products in chemical reactions while limiting undesirable byproducts by precisely designing these properties. Significant implications for the creation of environmentally friendly and long-lasting chemical processes result from this selectivity.

2. **Synthesis of Nanoparticle:** Nanoparticles have drawn considerable attention in the field of catalysis due to their distinct qualities and large surface area, which improve catalytic activity and selectivity. There are numerous ways to create these nanoparticles, having its own benefits and drawbacks. Physical methods, chemical methods, biological methods, and hybrid approaches can all be used to synthesize nanoparticles as catalysts (Reddy et al., 2016; Ali et al., 2021; Baig et al., 2021).

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2.1 Physical Method: A common method for creating nanoparticles is called sputtering, which involves bombarding a target substance with high-energy particles. Laser ablation is the process of melting a target material with a strong laser to create a plasma that condenses into nanoparticles. Physical vapor deposition (PVD) and electrodeposition are two other procedures that generate nanoparticles by precisely regulating the deposition of atoms onto a substrate. These methods may need pricey specialized equipment but can offer precise control over nanoparticle size and composition.

2.2 Chemical Methods: Chemical approaches are commonly utilized to produce nanoparticles due to their versatility and scalability. A reactant precipitates as a result of the mixing of two solutions to produce nanoparticles. Sol-gel synthesis produces nanoparticles from a precursor that resembles gel through the use of condensation and hydrolysis reactions. In microemulsion techniques, surfactants are used to provide the nanoscale reaction conditions that lead to the controlled production of nanoparticles. In the polyol process, metal precursors are converted to nanoparticles in a polyol solvent. Chemical techniques allow for the control of nanoparticle size, shape, and surface functionalization.

2.3 Biological approaches:

Nanoparticles can be prepared from biological method (plant and microorganism). Secondary metabolites of plants like polyphenolic, tanins, saponins and Microorganisms like bacteria and fungus can biochemically degrade metal ions to produce nanoparticles. Plant-mediated synthesis reduces and stabilizes nanoparticles by utilizing plant extracts rich in bioactive compounds. This procedure, which is also known as microbial synthesis or bioreduction, provides mild reaction conditions and is advantageous for the environment. Enzymatic synthesis is the process of producing nanoparticles with the aid of specific enzymes. Biological techniques are desirable because of their potential for green synthesis and sustainability.

2.4 Hybrid Approaches:

Hybrid approaches combine different synthesis processes in order to benefit from the distinctive qualities of each method. For instance, sonochemical synthesis accelerates chemical reactions with ultrasound to produce nanoparticles under control. Microwave-assisted synthesis, which accelerates chemical processes with microwave radiation, enables quick and efficient production of nanoparticles. Photochemical techniques use light irradiation to start chemical reactions that accurately control the

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properties of nanoparticles. Hybrid methods usually provide better control over particle size, shape, and content than separate methods.

In summary, several methods are employed to produce nanoparticles that function as catalysts, each of which has distinct advantages. Physical methods can require a lot of resources yet provide exquisite control. Techniques involving chemicals can be scaled and adjusted. Biological processes provide environmentally favorable alternatives. Hybrid methods combine many techniques to alter the characteristics of nanoparticles.

3. **Properties and Characterization of Nanoparticle:**

Nanoparticle catalysts have received interest due to their unique properties and potential applications in a number of industries, including catalysis, energy conversion, environmental remediation, and more. These catalysts have unique nanoscale properties that distinguish them from bulk materials, making them especially efficient and selective at catalyzing chemical reactions (Gawande et al., 2016, Ealia et al., 2017, Mourdikoudis et al., 2018).

3.1 Size- Dependent Catalytic properties: Nanoparticle catalysts have catalytic properties that depend on their size because of the different quantum and surface effects that emerge at the nanoscale. As nanoparticle size drops, a bigger proportion of atoms are located near the surface, leading to a higher density of catalytically active sites. The increased surface-to-volume ratio allows for the interaction of a greater number of reactant molecules with the active sites. Quantum events that can alter the electronic structure and consequently the catalytic action include the confinement of electrons and quantized energy levels. Size-dependent catalytic properties have been shown in a number of catalytic reactions, including CO oxidation, hydrogenation, and oxygen reduction reactions (Chen and Goodman, 2004; Zhou, et al., 2010, Haldar et al., 2014; Liang, et al., 2022).

3.2 Surface Area and Porosity: Critical characteristics of nanoparticle catalysts that significantly affect their catalytic effectiveness are their surface area and porosity. Nanoparticles provide more sites for reactant adsorption, effective mass transfer of reactants and products due to their large surface area and porosity. Greater exposure of active sites is made possible by the increased surface area to volume ratio, which enhances catalytic activity. To assess the surface area and porosity of nanoparticle catalysts, methods like BET (Brunauer-Emmett-Teller) analysis and TEM (transmission electron microscopy) are frequently used.

3.3 Morphology and Crystal structure: Nanoparticle shape and crystal structure affect the capacities of nanocatalyst. Different crystal facets and morphologies reveal different surface atom

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configurations, resulting in different catalytic actions. For instance, due to changes in atomic arrangement and binding strengths, different crystal facets may show increased activity or selectivity towards particular reactions. Controlled synthesis techniques, such as sol-gel, hydrothermal, or chemical vapor deposition, can be used to tailor the shape and crystal structure of nanoparticle catalysts (Xia et al., 2009).

The catalytic activity and selectivity of nanoparticle catalysts are greatly influenced by surface chemistry and active sites. Atomic configuration at the surface of nanoparticles effects reaction routes and the bonding of reactant molecules. The catalytic behavior can be changed by altering the surface chemistry, for as by adding new functional groups or heteroatoms. The surface chemistry and active sites of nanoparticle catalysts are examined using characterizing techniques such X-ray photoelectron spectroscopy (XPS) and Fourier-transform infrared spectroscopy (FTIR) (Peng and Yang, 2009).

4. Applications of Nanoparticle Catalysts: Nanocatalyst has vide applications in different sectors. They are incredibly effective at catalyzing chemical reactions due to their special qualities, which result from their small size and high surface area-to-volume ratio. Nanoparticle catalysts have showed potential in the field of water purification by degrading and eliminating pollutants from contaminated water sources, such as organic colors, heavy metals, and pharmaceuticals. For instance, when exposed to UV light, advanced oxidation processes (AOPs) using titanium dioxide (TiO_2) nanoparticles can effectively breakdown organic contaminants through photocatalytic reactions. By producing highly reactive species, these catalysts transform contaminants into less dangerous ones.

By facilitating the transformation of toxic gases like nitrogen oxides (NOx) and volatile organic compounds (VOCs) into less damaging chemicals, nanoparticle catalysts have shown promise in reducing air pollution. To boost the catalytic effectiveness of automotive catalytic converters, for instance, cerium oxide nanoparticles have been used (Somwanshi et al., 2020; Roy et al., 2021). This has improved the removal of pollutants from exhaust gases.

In the water splitting method of producing hydrogen, nanoparticle catalysts are essential. The production of hydrogen from water is made easier by catalysts like platinum (Pt) and iridium oxide (IrO_2) nanoparticles, which increase the effectiveness of electrolysis reactions. As a result of these catalysts' enhanced reaction kinetics and reduced energy requirements, clean and sustainable hydrogen fuel is being developed (Choi et al., 2016; Zhang et al., 2013).

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Conclusion

It is evident that nanoparticles are important as catalysts and have a lot of potential for use in a wide range of scientific, industrial, and environmental applications. They are able to catalyze processes effectively due to high surface area, improved reactivity and variable size. Increased reaction rates, decreased energy use, and minimal waste production have all been achieved as a result of using nanoparticles as catalysts.

References

1. Ali, A., Shah, T., Ullah, R., Zhou, P., Guo, M., Ovais, M., ... & Rui, Y. (2021). Review on recent progress in magnetic nanoparticles: Synthesis, characterization, and diverse applications. *Frontiers in Chemistry*, *9*, 629054.
2. Astruc, D. (2020). Introduction: nanoparticles in catalysis. *Chemical reviews*, *120*(2), 461-463.
3. Baig, N., Kammakakam, I., & Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. *Materials Advances*, *2*(6), 1821-1871.
4. Chaturvedi, S., Dave, P. N., & Shah, N. K. (2012). Applications of nano-catalyst in new era. *Journal of Saudi Chemical Society*, *16*(3), 307-325.
5. Chen, M. S., & Goodman, D. W. (2004). The structure of catalytically active gold on titania. *science*, *306*(5694), 252-255.
6. Choi, J. W., Wang, D., & Wang, D. (2016). Nanomaterials for energy conversion and storage. *ChemNanoMat*, *2*(7), 560-561.
7. Ealia, S. A. M., & Saravanakumar, M. P. (2017, November). A review on the classification, characterisation, synthesis of nanoparticles and their application. In *IOP conference series: materials science and engineering* (Vol. 263, No. 3, p. 032019).
8. Epelle, E. I., Desongu, K. S., Obande, W., Adeleke, A. A., Ikubanni, P. P., Okolie, J. A., & Gunes, B. (2022). A comprehensive review of hydrogen production and storage: A focus on the role of nanomaterials. *International Journal of Hydrogen Energy*, *47*(47), 20398-20431.

ISBN : 978-93-91535-95-7

9. Gao, C., Lyu, F., & Yin, Y. (2020). Encapsulated metal nanoparticles for catalysis. *Chemical Reviews*, *121*(2), 834-881.

10. Gawande, M. B., Goswami, A., Felpin, F. X., Asefa, T., Huang, X., Silva, R., ... & Varma, R. S. (2016). Cu and Cu-based nanoparticles: synthesis and applications in catalysis. *Chemical reviews*, *116*(6), 3722-3811.

11. Gupta, K., Kaushik, A., Tikoo, K. B., Kumar, V., & Singhal, S. (2020). Enhanced catalytic activity of composites of NiFe2O4 and nano cellulose derived from waste biomass for the mitigation of organic pollutants. *Arabian Journal of Chemistry*, *13*(1), 783-798.

12. Haldar, K. K., Kundu, S., & Patra, A. (2014). Core-size-dependent catalytic properties of bimetallic Au/Ag core–shell nanoparticles. *ACS applied materials & interfaces*, *6*(24), 21946-21953.

13. Iravani, S., Korbekandi, H., Mirmohammadi, S. V., & Zolfaghari, B. (2014). Synthesis of silver nanoparticles: chemical, physical and biological methods. *Research in pharmaceutical sciences*, *9*(6), 385.

14. Kushwah, M., Bhadauria, S., Arora, K., & Gaur, M. S. (2019). Enhanced catalytic activity of chemically synthesized Au/Ag/Cu trimetallic nanoparticles. *Materials Research Express*, *6*(9), 095013.

15. Li, J., Wang, Q., Yu, S., Wei, Z., & Zhang, H. (2022). Highly Dispersed Pd Nanoclusters on Layered Double Hydroxides with Proper Calcination Improving Solvent-Free Oxidation of Benzyl Alcohol. *ACS Sustainable Chemistry & Engineering*, *10*(22), 7223-7233.

16. Liang, C., Cheong, J. Y., Sitaru, G., Rosenfeldt, S., Schenk, A. S., Gekle, S., ... & Greiner, A. (2022). Size-Dependent Catalytic Behavior of Gold Nanoparticles. *Advanced Materials Interfaces*, *9*(4), 2100867.

17. Mao, S. S., Shen, S., & Guo, L. (2012). Nanomaterials for renewable hydrogen production, storage and utilization. *Progress in Natural Science: Materials International*, *22*(6), 522-534.