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NANOCATALYSTS-NOVEL NANOENTITIES

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ABSTRACT

Because of their special qualities, nanocatalysts are employed to accelerate catalytic reactions. It is a better option for catalysis because of features like exposed active sites and a larger surface area than conventional catalysts. Metal, metal oxide, and hybrid nanocatalysts are the three standard categories for nanocatalysis. For example, metal nanocatalysts, such as palladium nanoparticles, have a large surface area and are highly dispersible, which significantly boosts reaction rates. While metal oxides, like $CoFe_2O_4$, have a high degree of thermal stability, hybrid systems combine the best features of both to improve reactivity and selectivity in a variety of applications, such as oxidative desulfurization.

KEY WORDS: Catalytic;Nanoscale; Sol–gel synthesis;Economical; Industrial Efficiency.

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INTRODUCTION

Compared to their conventional counterparts, nanoscale materials exhibit greater catalytic activity due to their ability to withstand surface strain, optimize atomic shape, and improve atom consumption [1]. Studies have demonstrated that materials can dramatically alter electronic characteristics by shrinking metal particles to the nanoscale, improving the scalability and effectiveness of catalytic reactions in a variety of fields, such as energy and environmental applications [2].

Designing of Nanocatalysts

Various approaches to developing single-atom and nanocatalysts are depicted in Figure 1.

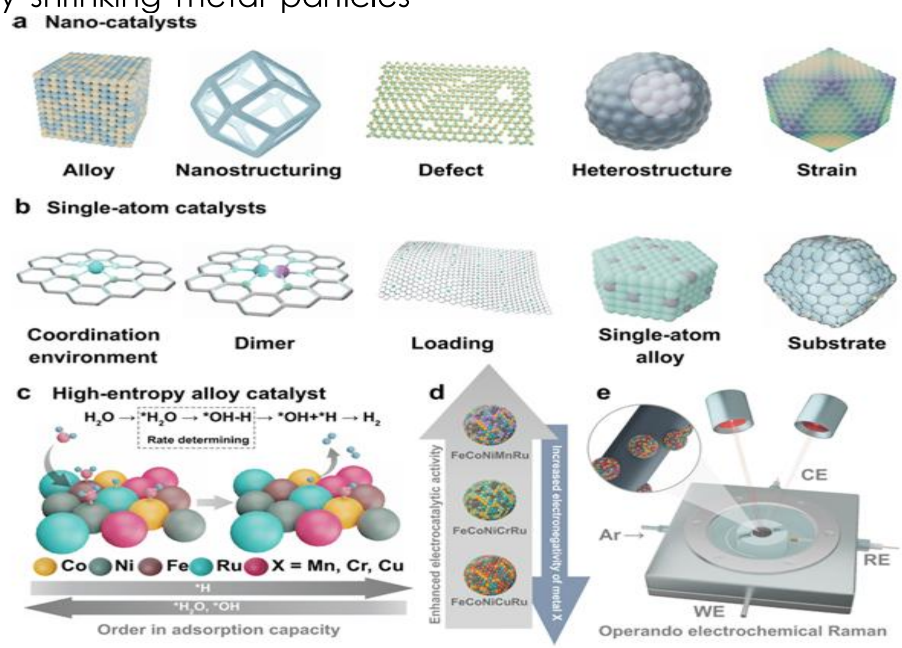

Figure 1: Concepts of designing Nanocatalysts: As illustrated in the given parts below

(a) A variety of nano-catalyst design such as heterostructures with unique material interfaces, alloys of mixed metal atoms, strain application to improve electronic properties, defect introduction to improve active sites, and nanostructuring for increased surface area.

(b) The coordination environment of isolated metal atoms on a support, dimerization, single-atom deposition on a substrate, single-atom alloys in which single atoms are distributed across a host metal lattice, and substrate material

(c) A high-entropy alloy catalyst, along with the order of adsorption capacity for various metal constituents (Co, Ni, Fe, Ru, and generic metal X), as well as the adsorption of water molecules and the suggested rate-determining phase in a catalytic process.

(d) A triangular plot illustrating the increased electrocatalytic activity of high-entropy alloys with varying Fe, Co, Ni, andRu and Mn.

(e) An operando electrochemical Raman setup, illustrating how the working electrode (WE) with a loaded catalyst is probed using counter (CE) and reference (RE) electrodes under reaction conditions while Raman spectroscopy is recorded and argon (Ar) gas is purged.

Synthesis Techniques of Nanocatalysts

Typically, methods including sol-gel, hydrothermal, and green synthesis are used to create nanocatalysts [3]. Similar to nano $MgCuAl_2O_5$ production, sol–gel synthesis permits control over phase purity and particle size [4]. For the creation of metal oxide nanocatalysts, hydrothermal synthesis has been shown to yield good crystallinity and uniform shape at lower temperatures [5]. Green synthesis uses natural reducing agents, such as plant extracts, to create nanocatalysts in an economical and environmentally responsible manner. The procedure reduces hazardous byproducts and is in line with current worldwide, including Pakistan, trends in sustainable chemical processing [6]. Furthermore, by promoting reaction kinetics and reducing energy consumption, microwave-assisted procedures improve synthesis efficiency [7]. With improved performance and environmental protection, all of these procedures advance the new paradigm of nanocatalyst manufacturing.

Three important approaches to nanoparticle synthesis are shown in Figure 2.

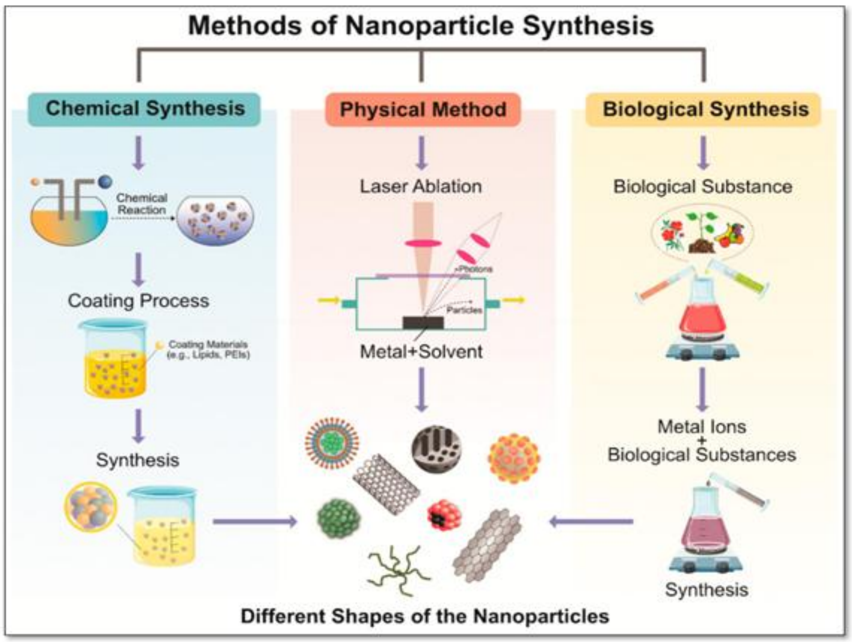

Figure 2: Synthesis Techniques of Nanocatalysts

As illustrated in the given figure Chemical synthesis combines a coating procedure with a chemical reaction. It makes use of substances like lipids and polymers. The final step entails creating the nanoparticles in a solution. On the other hand Physical techniques, such as laser ablation, include using a laser to irradiate a metal target suspended in solvent in order to create nanoparticles. Utilizing biological sources, such as plant or microbe extracts, biological synthesis creates nanoparticles by binding with the metal ions.

Applications in Environmental and Industrial Processes

In recent years, nanocatalysts have shown promising real-world applications in environmental and industrial processes. Pt-based nanocatalysts have shown promise in pollutant degradation, enabling advanced wastewater treatments and efficiently reducing toxicants such as 4-nitrophenol [8].Furthermore, real-time water decontamination is made possible by novel structures like MOF@flexible filter sheets, however MOF mass production issues persist [9]. According to recent studies, methane-fueled reactors enhanced with nanocatalysts have higher conversion rates in the production of hydrogen [10].Furthermore, citing improved catalytic processes, electrocatalysts derived from anion-tuned nickel chalcogenides have allegedly been utilized to facilitate effective oxygen reduction reactions in fuel cells and H_2O_2 production [11]. Numerous industrial uses for hybrid nanocatalysts are depicted in Figure 3.

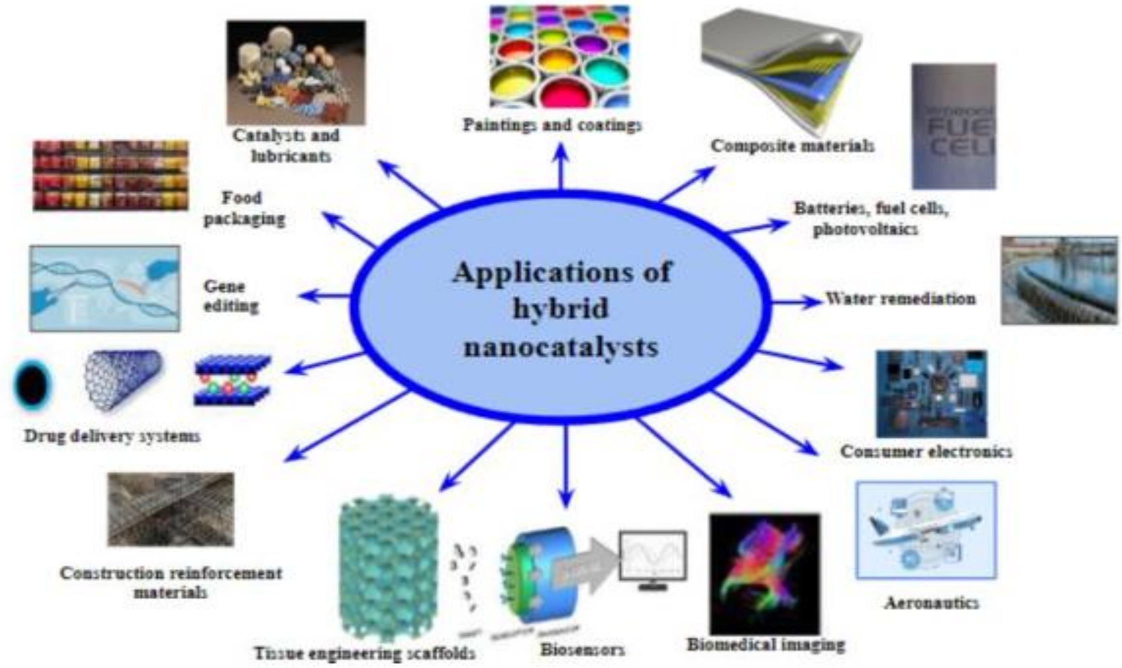

Figure 3: Applications of hybrid nanocatalysts

Nano Catalysis Research in Pakistan (2022–2025)

In Pakistan, nanocatalysis research has been concentrating more on environmental and energy-related problems between 2022 and 2025, such as wastewater treatment,biodieselprocessing and solar-driven catalysis [12]. Researchers have created novel photo/electric and triboelectric coupling methods for wastewater treatment that improve pollutant degradation while lowering secondary waste [13]. Advances in catalytic selectivity enhancement, process sustainability, and enzyme encapsulation strategies have all influenced biodiesel processing developments [14]. As photothermal and photocatalytic materials are made to use the entire spectrum of the sun, solar-driven catalysis is also undergoing innovation [15]. Leading institutions spearheading these research initiatives include NUST, COMSATS, and PCSIR. However, these initiatives face significant obstacles like scarce resources, equipment limitations, and scaling up, which is why more policy facilitation and international coordination are needed to close the gap between laboratory success and industry production [16, 17].

Nano Catalysis Research in Foreign Countries (2022–2025)

Unprecedented advances in technologies that use artificial intelligence (AI) to rationalize catalysts, atomically accurate synthesis processes, and the design of dual-function nanomaterials have defined international nanocatalysis research in 2022–2025 [18]. Researchers in leading countries including China, the USA, and Germany have accelerated the identification of catalysts with specific selectivity and increased energy efficiency by rationalizing catalyst active sites using AI-driven computational resources [19]. At the same time, advances in the atomically precise manufacturing of catalysts have opened up new possibilities for electrocatalytic processes and advanced carbon neutrality and sustainability in energy conversion systems, as evidenced by a number of research employing well-defined metal clusters [20]. Furthermore, because of the synergistic nature of their active sites, which facilitate multi-electron transfer processes, dual-atom catalysts (DACs) have emerged as a cutting-edge technology with promising results for oxygen evolution reactions and other energy-related catalysis [21]. The innovations are combined with a broad focus on sustainability, where an attempt is made to design to maximize overall energy efficiency and reduce carbon emissions during catalytic reactions [22].

Comparative Analysis: Pakistan vs Foreign Research

A comparative analysis of nanocatalysis research conducted in Pakistan and around the world reveals both strengths and limitations in terms of financing, publications, research capabilities, and international collaboration. Despite cutting-edge research on atomically precise and dual-atom, Pakistani scientists have typically concentrated on applied research in wastewater treatment, biodiesel, and solar-driven catalysis, while countries like China, the USA, and Germany are heavily investing in state-of-the-art manufacturing technology and computational design software [23]. Despite the fact that these applications demonstrate the creative use of locally accessible resources and environmental requirements, Pakistani research is usually constrained by a lack of adequate funding, adequate high-tech facilities, and scale-up problems that prevent the scale-up from laboratory-scale models to industrial scales [24,25]. This discrepancy emphasizes the necessity of more international collaboration and funding for Pakistani research centers and collaborative studies.

Conclusion

Nanocatalysis has enormous potential to support green energy technologies and a circular economy in the years to come. Catalytic and plasmonic dual-functional nanomaterials can facilitate new chemical transformations necessary for carbon neutrality as well as more effective solar-driven reactions. It is recommended that Pakistani officials establish robust policy support and foster industry-academia links that facilitate the commercialization of novel catalytic systems in order to take advantage of these potential. To close the current gap in cutting-edge nanocatalysis techniques, it is also essential to develop skilled people resources through targeted education and research initiatives. Adopting the research approaches of world leaders, especially in fields like atomically precise catalyst engineering and AI-assisted design while coordinating research objectives with sustainable development objectives, might significantly improve Pakistan's standing in international nanocatalysis research.

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