

A Critical Review of Nanoparticles and Nano Catalyst

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Abstract – Catalysis holds a significant position in the field of chemistry, wherein it manifests in three distinct directions that exhibit minimal overlap: heterogeneous, enzymatic, and homogeneous. Heterogeneous and homogeneous catalysis are recognized as distinct fields championed by two scientific societies, namely solid state and molecular chemistry. Despite their differences, both domains share a common goal of seeking to enhance catalytic performance. Nanocatalysis has gained prominence as a burgeoning scientific discipline in recent times, owing to its exceptional levels of activity, selectivity, and productivity. The distinctive characteristics of nanocatalysts arise from their nanoscale dimensions, morphology, and significantly elevated surface area to volume ratio. These structural and electronic modifications distinguish them from their bulk counterparts, resulting in unique properties. At the nanoscale level, the principles of quantum chemistry and classical physics are not applicable. In materials characterised by robust chemical bonding, the degree of electron delocalization can be substantial and may exhibit size-dependent variability. The primary objective of this review is to expound upon the critical understanding of nanocatalysis, detailing how the different catalytic feature and other particle features of nanomaterials are contingent on their structure and size at an atomic level.

Keywords – Nanoparticles, Nanomaterials, Nanoscience, Carbon Nanotubes, Homogeneous Catalysis, Heterogeneous Catalysis.

I. INTRODUCTION

The significance of catalytic technologies is paramount in the current and forthcoming energy, chemical process, and environmental sectors. Catalytic technologies play a crucial role in various industrial processes such as crude oil, natural gas, and coal conversion into chemical feedstock and fuels, the generation of chemical products, and diverse petrochemical, and controls of hydrocarbons, NO, and CO emissions. Catalysts are a crucial element in the composition of electrodes utilised in fuel cells, which operate on either polymeric proton electrolyte or solid oxide ionic. The enhancement of advanced catalysts is driven by several factors, including the desire to produce high-value products using cost-effective raw materials, the need for chemical conversion processes that are both energy-efficient and environmentally-friendly, the implementation of increasingly strict environmental regulations, and the employment of low-cost catalysts, which integrate the replacement or reduction of precious metals.

Catalysis involves the acceleration of chemical reactions in solid, gaseous, or liquid phases through the introduction of a solid phase. This solid phase is designed to contain a sufficient quantity of appropriate sites for chemical reactants to desorb, react, and absorb. In order to optimise the catalyst, it is necessary to increase the number of sites and expand the surface area. This could be attained by minimizing the size of the catalytic particles. Presently, in modern laboratory settings, the prevalent form of active catalysts comprises of meticulously crafted particles that are of nanometer dimensions, situated on supports that possess pores or structural characteristics of similar nanometer scale. Contemporary catalysts are commonly composed of active phases comprising multiple components, which may incorporate a support designed to facilitate the dispersion, isolation, or augmentation of the characteristics or structure of individual catalytic elements. The main purpose of catalysis study is to comprehend the impact of reducing the size of catalytic particles on their inherent catalytic activity, which extends beyond the mere augmentation of surface area. One of the objectives is to acquire knowledge on the development and production of catalysts that possess optimal size and structure.

The potential utility of nanoscience in a vast array of domains is an intriguing prospect. Advancements in nanotechnology have the potential to benefit various fields, including medicine, electronics, manufacturing, and fashion. The multifaceted application of nano-scale technology is noteworthy, with the utilisation of nanocrystals as catalysts being

particularly intriguing. The fundamental principle underlying the comprehension of nanocrystal catalysis pertains to the proportion of surface-area-to-volume (S/V). The relationship between the increase in surface area and volume of an object is inversely proportional, such that as the object's size increases, the rate of increase in surface area is comparatively lower than that of its volume. Thus, diminutive entities possess a greater surface area in relation to their volume. The aforementioned has significant ramifications for chemical reactions. Chemical reactions tend to be more favourable when there is a high S/V ratio. Regarding the campfire scenario, kindling is utilised as an ignition source for the fire. The high S/V ratio is higher in small pieces of wood as compared to larger logs. The act of igniting the kindling leads to an expedited combustion process.

Moreover, when an individual disperses a quantity of sawdust onto a combustion process, a substantial burst of flame ensues. The aforementioned reaction exhibits chemical equivalence to the conventional process of wood combustion, albeit with a significantly accelerated rate. Catalysts have the primary function of enhancing particular chemical reaction rate. The aforementioned process is accomplished via kinetic mechanisms and does not have a direct impact on the thermodynamic characteristics of a given chemical system. The acceleration of a chemical reaction can be achieved through the use of a catalyst, which operates via one of three mechanisms: reducing the activation energy required for the reaction, enhancing the efficacy of the reactive species' interaction through facilitation, or promoting the production of a specific species when multiple products are generated. Nano-catalysts could be utilised in all the aforementioned mechanisms, contingent on the specific application. There are two primary reasons why nano-materials exhibit greater efficacy than conventional catalysts: (i) the diminutive dimensions of nanoparticles, which are typically within the range of 10-80 nm, result in an exceptionally high S/V ratio; and (ii) the fabrication of materials at the nanoscale results in the emergence of distinct properties that are absent in their macroscopic counterparts. The versatility and effectiveness of nanocatalysts can be attributed to both of these factors.

The primary objective of this review is to explicate the critical understanding of nanocatalysis, elucidating how the distinctive catalytic feature as well as other particular nanomaterials features are contingent upon their structure and size at the atomic level. The subsequent section of this document is structured in the following manner: Section II presents a background analysis of the research. Section III analyses the chemistry of nanoparticles, while Section IV focuses on nanocatalysis. In Section V, a discussion of the concept of nanocatalysis is provided, in which the influence of intrinsic characteristics of nanomaterials on catalysis is discussed. Section VI focuses on homogeneous and heterogeneous nanocatalysis, with concepts of carbon nanotubes, water purification and bio-diesel production, discussed. Lastly, Section VII draws a conclusion to the article, as well as future research directions.

II. BACKGROUND ANALYSIS

The utilisation of catalysis is of utmost importance in chemical transformations and serves as a fundamental component in numerous chemical procedures, ranging from academic study done in lab settings to the chemical sector at large. The utilisation of catalytic reagents has the potential to decrease the temperature required for a chemical transformation, minimise the production of waste resulting from reagents, and augment the specificity of a reaction, thereby circumventing undesired side reactions and promoting environmentally sustainable practices. Llored and Sarrade [1] recommended a collection of 12 principles, which form the major green chemistry philosophy. These principles aim to mitigate or eradicate chemicals and chemical processes that have adverse environmental effects. The conception of green chemistry places great significance on the creation and refinement of optimal catalysts. Based on these principles, it can be argued that catalytic reagents, which exhibit high selectivity, are more advantageous than stoichiometric reagents. Stoichiometric reagents are utilised in surplus and exhibit a singular reaction, whereas catalytic reagents are employed in minute quantities and have the ability to facilitate multiple reactions. The fundamental basis of the 12 principles of the green chemistry is to emulate the workings of nature.

The utilisation of micro-organisms and/or enzymes in conducting environmentally friendly reactions is evidently suggested by nature. The production of a diverse range of products, including fine chemicals, fibres, medicines, polymers, fuels, lubricants, paints, and different value-added products that are crucial to human needs, could not be viable in the absence of a catalyst. Catalysis plays a crucial role in facilitating chemical reactions, thereby enabling the production of desired materials on a commercial scale. The utilisation of catalysts can lead to the enhancement of economic, environmental, and sustainable manufacturing protocols. In addition to heavy metal catalysts, which are typically unrecoverable from the system, there has been a growing interest in the use of softer catalysts such as zeolites and phase transfer catalysts like crown ethers, due to their increased industrial applicability. Enzymatic catalysis is widely recognised as the most efficient and environmentally friendly form of catalysis among the three prominent categories, namely homogeneous, heterogeneous, and enzymatic catalysis. Both homogeneous and heterogeneous catalysis possess advantages and disadvantages, necessitating the development of a novel catalytic system that exhibits the activity of homogeneous catalysis while also being readily recoverable like heterogeneous catalysts.

Nano-catalysts have the integrated advantages of heterogeneous and homogeneous catalytic models. The utilisation of a nano catalytic system enables expeditious and discriminating chemical conversions, resulting in exceptional product output, while simultaneously facilitating the effortless separation and retrieval of the catalyst. The retrieval of catalysts from a system is a crucial feature that any catalyst must possess in order to be deemed suitable for employment in eco-friendly chemical production procedures within the industrial sector. Because of the large surface area of nanoscale

objects, there is a huge increase in the amount of contact between the reactants and the catalyst (a phenomenon similar to homogeneous catalysis). The catalyst could be separated with ease from the reaction mixtures due to its heterogeneity caused by insolubility in the reaction solvent, which bears resemblance to heterogeneous catalysis as reported in literature.

III. CHEMISTRY OF NANOPARTICLES

Nanoparticles (NPs) are referred to as the particles composed of dimensions that range from 1 to 100 nanometers (10⁻⁹ metres). The primary objective of nanochemistry is to synthesise nanoparticles that are stabilised and fall within the 1-100 nm size range. The synthesis of nanoparticles can be grouped into two main groups: bottom-up technologies and top-down technologies (**Fig 1**).

Different advanced tools have been employed to characterize nanomaterials to regulate their shape, size, valency, surface structure, electron band gaps, chemical composition, light emission, bonding ecosystem, scattering, absorption, and diffraction features. The tools integrate infrared spectroscopy (IR), transmission electron microscopy (TEM), nuclear magnetic resonance spectroscopy (NMR), scanning electron microscopy (SEM), ultraviolet and visible spectroscopy (UV-Vis), scanning tunnelling microscopy (STM), X-ray diffraction (XRD), energy dispersive X-ray spectrometry (EDS), ultraviolet photoelectron spectroscopy (UPS), X-ray photoelectron spectroscopy (XPS), extended X-ray absorption fine structure spectroscopy (EXAFS), X-ray emission spectroscopy (XES), X-ray absorption near-edge spectroscopy (XANES), photoluminescence spectroscopy (PL), atomic force microscopy (AFM), and small angle X-ray scattering (SAXS).

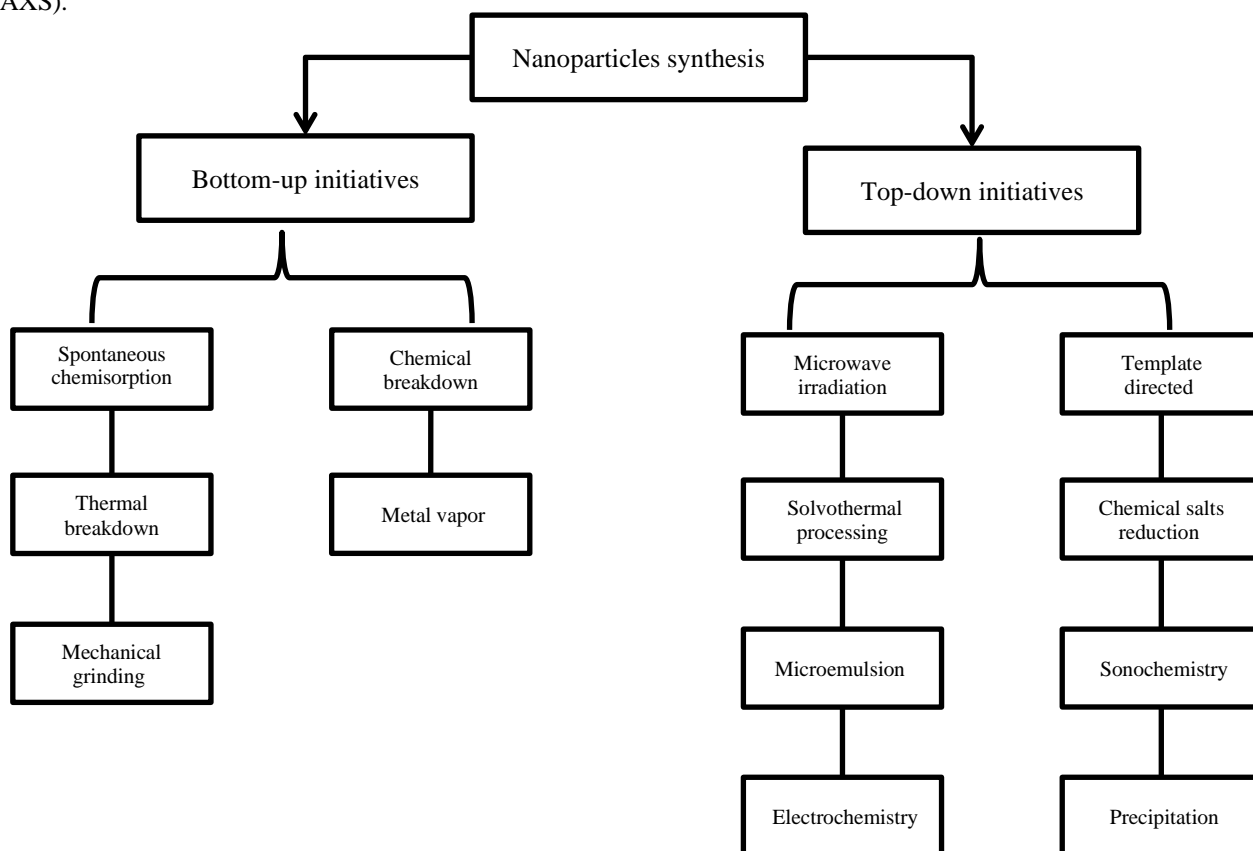


Fig 1. Different Mechanisms to Synthesize Nanoparticles

The chemistry of nanoparticles is primarily influenced by two factors: the controlled synthesis of nanoparticles in terms of their shape and size, and the molecular mechanism to determine more categorical applications of nanoparticles, particularly in the field of nanocatalysis. The definition of nanoparticles is restricted by their size, which has implications for their chemical properties. The production of nanoparticles with precise size control is primarily achieved through the utilisation of various capping or stabilising agents, including ligands (i.e., amines, thiols, and phosphines), polymers (i.e., block-copolymers, polyvinyl pyrrolidone, polyvinyl alcohols), and surfactants (i.e., ammonium salts) dendrimers (i.e., polyamidoamine), polyoxoanions, and ions, among others.

The selection of suitable stabilising and protecting agents is a crucial aspect that can significantly impact the surface characteristics of nanoparticles. This is due to the potential for these agents to modify the surface chemical ecosystem and active site morphology via electronic or/and steric effects. The critical importance of the selectivity and reactivity of nanoparticles lies in their ability to affect the line of a specific reaction that is majorly reliant on the nanoparticle's surface state. The selectivity and reactivity of nanoparticles are primarily determined by two factors: (i) the regulation of crystal

morphology and structure, and (ii) the surface composition regulations. The activity of nanoparticles is a matter of interest with regards to the surface structure, the exposure of various crystallographic facets, and an increased number of edges, corners, and faces.

Hence, the proficient regulation of nanoparticle morphology has emerged as a compelling objective worldwide in contemporary times. Furthermore, the intrinsic composition of NPs can be manipulated to modify their selectivity. The synthesis of bimetallic nanoparticles, specifically core-shell versus alloyed structures, the copper-based nanoparticles synthesis with a precisely defined surface state are critical areas of focus in contemporary nanoscience research and development. The field of nanocatalysis is currently experiencing growth and development in the area of bimetallics. The researchers anticipate demonstrating not only the amalgamated characteristics of two disparate metallic elements, but also new features and functionalities arising from a synergistic interaction between the two metallic elements.

The methodologies utilized the Cu-based nanoparticles synthesis typically draw upon the same procedures that have been utilised in the production of nanoparticles composed of other metals. The majority of techniques employed in the synthesis of nanoscale materials can be classified as either "bottom-up" or "top-down". The former involves the utilisation of atomic-level precursors to create the desired nanosized materials, while the latter involves the gradual reduction of a bulk solid into smaller and smaller components. Although each method has its own set of benefits and drawbacks, the bottom-up approach has gained more traction due to its ability to provide a wider range of control over the morphology and dimensions of the resulting nanoparticles. Furthermore, the propensity of copper nanoparticles (Cu NPs) to go through oxidation stimulates the establishment of copper oxide nanoparticles (NPs) that are more stable in numerous instances. The challenge of categorising the synthetic methodologies utilised in the production of nanomaterials primarily arises from the similarity of the correspondent chemical reactions. The copper oxide nanoparticles (NPs) and copper (Cu) synthesizing process primarily involves four distinct chemical reaction types, which are condensation, oxidation, reduction, and hydrolysis. The implementation of a combination or single aforementioned chemistries is contingent upon the selection of final materials.

The process of producing copper nanoparticles frequently involves the reduction of sources containing either Cu(I) or Cu(II). The generation of Cu nanoparticles entails a hydrolysis reaction of the precursors, which is subsequently succeeded by the dehydration procedure that culminates in the formation of the ultimate materials. Furthermore, the utilisation of an oxidation process that could be inevitable for copper-based nanoparticles can be employed to synthesise copper-based nanoparticles with elevated oxidation values from their respective precursors of low states of oxidation.

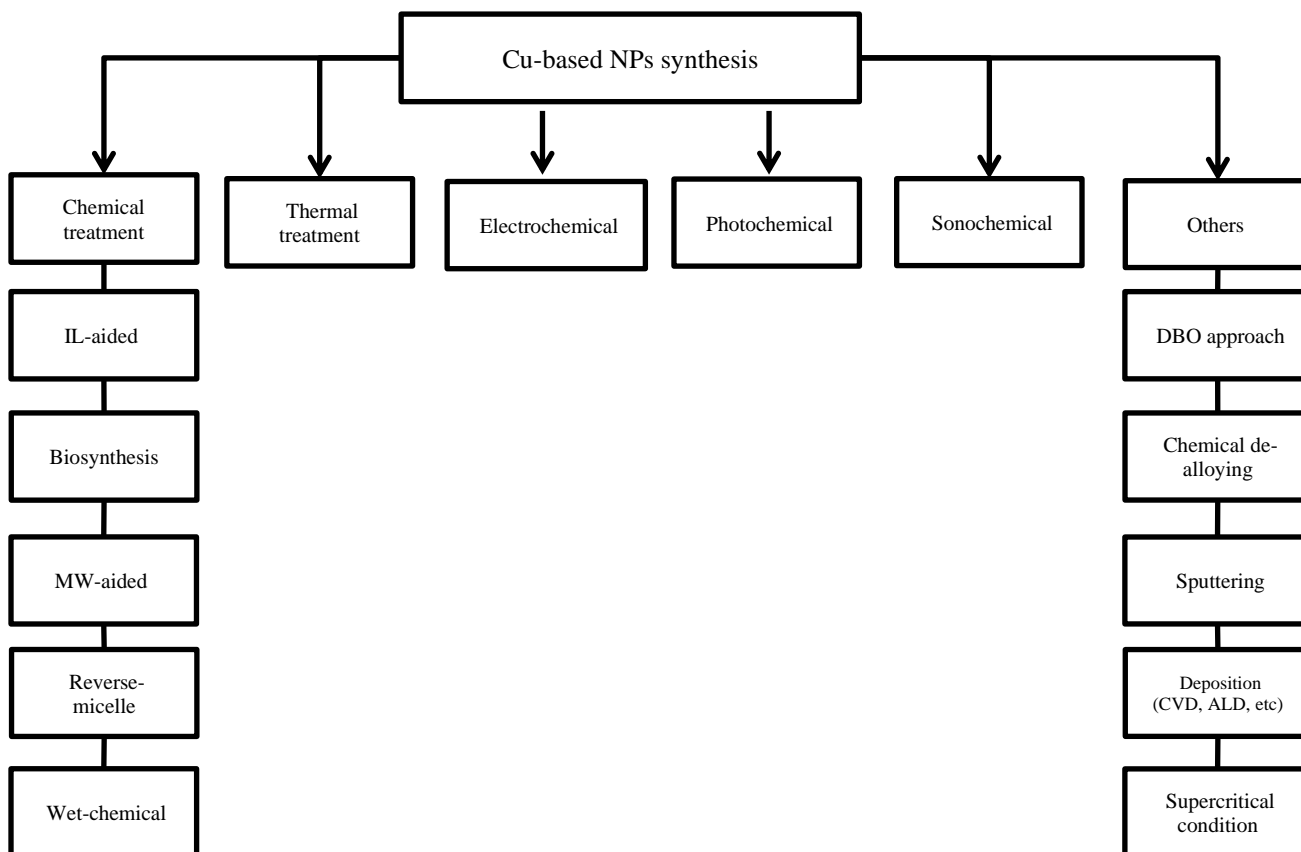


Fig 2. Main synthetic methodologies for the preparations of nanomaterials that are based on Cu [dielectric battery discharge (DBD), ionic liquid (IL), atomic layer deposition (ALD), chemical vapor deposition (CVD), and

Microwave (MW)].

The techniques utilised in synthetic processes create an appropriate setting and energy to facilitate the desired process, while also imposing additional constraints to regulate the stability, properties, and morphology of the resulting nanoparticles. The categorization of methods for synthesising Cu-based nanomaterials is based on literature precedence and could be grouped into 5 main groups: electrochemical synthesis, chemical treatment, photochemical techniques, thermal treatment, and sonochemical methods as depicted in **Fig. 2**. The category denoted as "others" encompasses advanced methodologies that have been lately documented and are gaining prominence.

The most widely used technique among these is the chemical treatment method. Some of the contemporary approaches can be considered as an expansion of this protocol, offering benefits in the aspect of selectivity of size or/and shape. **Fig. 2** provides a brief overview of significant examples pertaining to the Cu NPs synthesis, wherein peripheral reducing agent has been predominantly utilised, as well as Cu NPs. The "wet chemical" methodology is a state-of-the-art method utilised for the synthesis of metallic copper nanoparticles. This technique primarily involves the use of a reducing agent, which furnish electrons of reducing the copper salt, such as CuSO_4 , $\text{Cu}(\text{NO}_3)_2$, CuCl_2 , and copper(II) acetylacetonate. The reduction of compounds is commonly achieved through the use of various reducing agents, such as hydrazine, sodium borohydride, 1,2-hexadecanediol, ascorbic acid, glucose, borane compounds, or CO. Several capping agents have been employed to stabilise the resulting Cu nanoparticles and regulate their growth.

The reverse micelle method is a viable option that entails the creation of O/W (oil-in-water) microemulsion via the integration of surfactants to vessels with non-polar and polar solvents, which are immiscible. The reverse micelle structure wherein the hydrocarbon tails extend into the polar head group sphere and the oil phase encloses a minimal amount of an aqueous stage in the interior core. The reverse micelles have the potential to function as nanoreactors with uniform size, facilitating the production of nanoparticles with controlled shape and size. By manipulating the reaction parameters to generate micelles with varying dimensions, it is possible to modulate the size of the resultant nanoparticles. In this study, Ammal and Heyden [2] employed the methodology established to synthesise Cu nanoclusters of metallic nature. The microemulsion system utilised in this synthesis was composed of sodium dodecyl sulphate (SDS), or sodium lauryl sulphate (SLS) as surfactants, cyclohexane as oil phases, isopentanol as cosurfactants, and an aqueous CuSO_4 solution of the copper source. Following the reduction of oxygen from systems via nitrogen purging, a sparse aqueous sodium borohydride solution was introduced for simulate the establishment of the colloidal copper cluster, resulting to the creation of colloidal copper nanomaterials.

The surface chemistry of nanocrystals is a determining factor in their properties. The implementation of ligands or diatoms to adorn the surface of nanoparticles can result in novel catalytic characteristics, as evidenced by chemical alterations. It can be inferred that the chemical properties of nanoparticles can be altered through the selection of suitable capping agents, based on their respective electronic and steric properties. The utilisation of chiral capping agents in asymmetric catalysis is a crucial aspect, particularly in stabilising metallic nanoparticles, as it is anticipated to elicit enantioselectivity. Advancements in the efficacy of metallic nanoparticles have been accompanied by advancements in their retrieval and reusability.

The recyclability of catalysts presents a significant obstacle for the implementation of nanoparticles in the solution phase for industrial purposes. In order to achieve the desired outcome, researchers are currently investigating the technique of depositing pre-formed nanoparticles onto a range of supports including ceria, clay, titania, biowaste materials, alumina, silica, and other oxides, including carbon supports in different types such as mesostructured silica, carbon nanotubes and alumina membranes. This approach aims to create heterogeneous systems that are easily recoverable. In recent years, a novel approach has emerged involving the utilisation of magnetic supports for the retrieval of catalysts from catalytic media through the application of a magnetic field. Magnetic separation has been acknowledged as an efficient, expeditious, and reliable separation technique with numerous benefits in comparison to other chemical or physical methods for isolating products/catalysts, including chromatography, liquid-liquid extraction, distillation, centrifugation, or filtration. The immobilisation of the super-paramagnetic nanomaterials catalyst facilitates its separation from products due to robust interactions between externally employed magnetic fields and magnetic nanoparticles. Furthermore, the catalyst could be readily re-dispersed in magnetic field absence, as a result of the lack of magnetic memory.

IV. NANO-CATALYSIS

The utilisation of nanoparticles in catalysis represents a pioneering application in the field. For several years, catalysts in nanoscale have been utilised, including but not limited to components and materials such as clays, silica, titanium dioxide, iron, and aluminium. However, a comprehensive understanding of the remarkable catalytic activities unveiled by NPs has yet to be fully elucidated. The significant NPs' surface area has a direct and favourable impact on the rate of reaction and could potentially account for its catalytic properties. The catalytic activities of materials could be affected by its structural and shape-based characteristics at the nanoscale level. The optimisation of nanocatalysts, with regards to their composition (including bimetallic and core-shell types, as well as the application of supports), size, and shapes has resulted in improved selectivity. The inquiry at hand pertains to the correlation between the physical characteristics of nanoparticles and their catalytic characteristics, as well as the impact of manufacturing parameters on said physical characteristics.

Enhanced comprehension of these factors enables a scientist to devise nanocatalysts that exhibit exceptional levels of activity, selectivity, and durability. The aforementioned benefits have the potential to enhance the resource efficiency of industrial chemical reactions, reduce energy consumption, and minimise waste generation. This, in turn, can mitigate the environmental consequences associated with our dependence on chemical processes. Nanoparticles are widely acknowledged as a crucial catalyst in industrial settings, with a broad range of applications spanning from chemical production to the conversion and storage of energy. The heterogeneous nature of nanoparticles and their variations in size and shape are responsible for the particle-based catalytic activities and variables. **Fig. 3** illustrates the fundamental contrast between catalysis and bulk catalysis demonstrated by nanoscale materials.

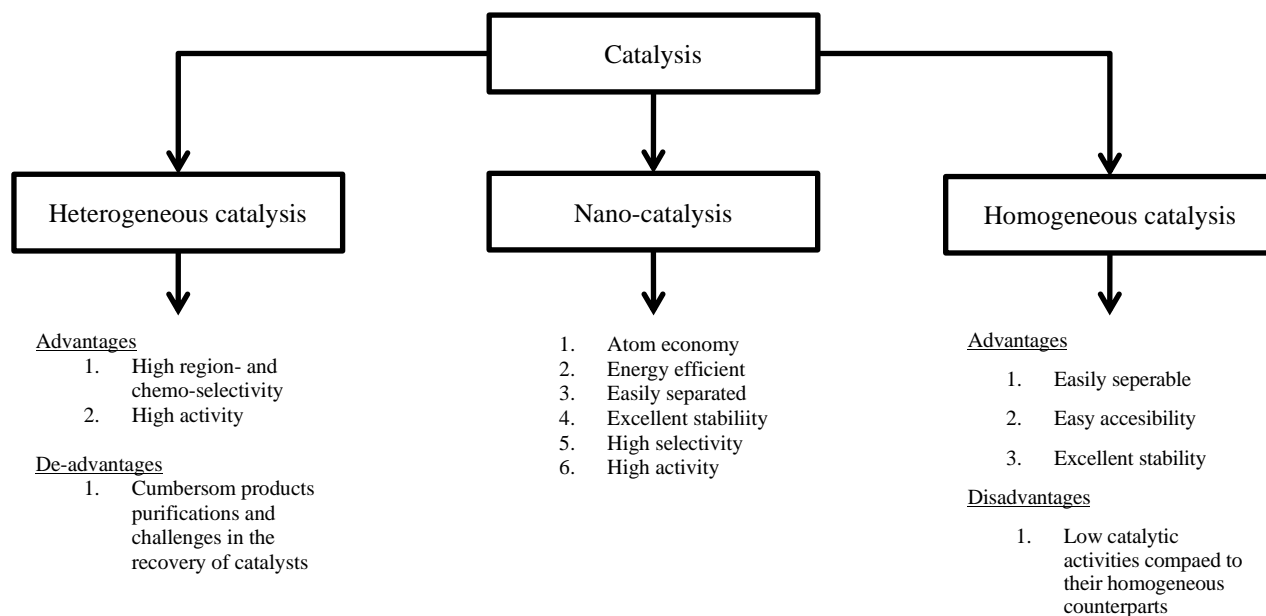


Fig 3. Comparative Effectiveness of Heterogeneous, Nanocatalysis and Homogeneous

V. CONCEPT OF NANOCATALYSIS

The underlying principle of nanocatalysis can be comprehended by examining the influence of the intrinsic characteristics of nanomaterials on catalytic processes. The intrinsic characteristics of nanomaterials play a crucial role in determining their catalytic efficacy.

The Influence of Intrinsic Characteristics of Nanomaterials on Catalysis

The performance of a cluster of atoms or a solid is influenced by interatomic interaction, resulting in variations from the performance of an isolated atom. The manipulation of the proportionate quantity of surface atoms that are under-coordinated presents an added degree of flexibility, enabling the fine-tuning of a nanosolid's characteristics in relation to those of its bulk equivalent. Therefore, it is reasonable to deliberate the contributions of under-synchronized atoms and interatomic interaction as a means of bridging the gap between bulk atoms and isolated atoms on the basis of their physical and chemical characteristics. The significant effects of atomic synchronization reduction that integrates the deviations of bond orders, angle, and length, cannot be overstated. The unification of surface, solid, and nanosolid performance in amorphous condition is achieved through consistent consideration of bond relaxation and its effects on the bond power,

The anomalous conduct of a nanosolid and a surface has been comprehensively comprehended and methodically expressed as variables of atomic coordination reduction and its byproducts (such as size dependence) on the atomic conning potentials, electron-phonon coupling, and crystal binding intensity. The determination of the functional relationship between a measurable parameter, Q , and atomic separation or its derivatives would lead to a conclusive understanding of the dependence of sizes of the parameter Q . Therefore, it is possible to create a nanomaterial with specific functionalities by utilising these predictions. Solid materials can typically be classified into distinct physical quantities, which include:

- a) Quantities that exhibit a direct correlation with bond length include the atomic density, binding energy, and the mean lattice constant. The lattice contraction phenomenon within a nanosolid amounts both surface relaxation and densification.
- b) Various physical properties are influenced by the cohesive power in each discrete atom. These integrate self-organization development, thermal stability, Coulomb blockade, fundamental temperature of stage transition, nanosolid evaporation, and the activation power for atomic dislocation, chemical reaction, and diffusion.

- c) The relaxed continuum region exhibits varying properties based on the binding energy density, including the Hamiltonian which governs the overall band network and interlinked features such as core level power, band gap, photoemission, and photo-absorption.
- d) The mechanical properties of a nanosolid, including its surface energy, Young's modulus, surface stress, compressibility, and extensibility, including its magnetic performance of a nanosolid that is a ferromagnetic are affected by the joint influence of the atomic cohesive energy and density of the binding energy.

The process of structural miniaturisation has provided a novel degree of flexibility, enabling the manipulation of physical properties that were previously considered invariant in larger structures. This is achieved through alterations in shape and size, which leverage the impact of reduced atomic coordination. The catalytic effects may be influenced by the intrinsic characteristics of nanomaterials and their dependence on size, as illustrated in Fig. 4.

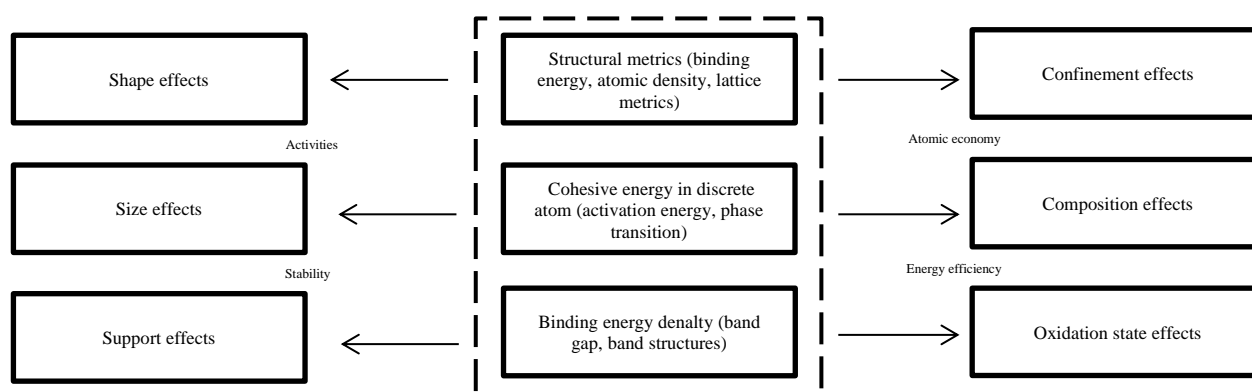


Fig 4. Intrinsic Characteristics of Nanomaterials

The solid materials performance or the clusters of atoms is different from that of isolated atoms primarily because of the inclusion of inter-atomic interactions. The manipulation of the proportionate quantity of surface atoms that are under-coordinated presents an added degree of flexibility, enabling the fine-tuning of the characteristics of a nanoscale solid in comparison to its larger-scale equivalent. Therefore, it is possible to initiate an investigation into the bridging of the gap between a bulk solid and an isolated atom on the basis of physical and chemical performance by taking into account the contribution of under-synchronized atoms and the participation of inter-atomic interactions. The significant effects of reducing atomic coordination, which involves changes in bond order, length, and angle, are noteworthy. The unification of surface performance, nano-solid performance, and solid performance in an amorphous state is achieved through consistent analysis of bond relaxation and its effects on the bond power.

The anomalous characteristics exhibited by a nano-solid and a surface have been comprehensively comprehended and methodically expressed as mathematical functionalities of the reductions in atomic coordination and its derivatives (which are dependent on size) on the potential for atomic trapping, the crystal binding intensity, and the coupling between electrons and phonons. The precise manipulation of various characteristics of individual nano-components, such as shape, size, spatial distribution, electronic structure, surface composition, chemical stability, and thermal stability can lead to their application in catalysis with higher activities and properties. The usage of nano-structured catalysts has garnered significant interest from both academic and industrial researchers in recent years, owing to the multitude of potential advantages that can be derived from their implementation.

VI. HOMOGENEOUS AND HETEROGENEOUS NANOCATALYSIS

In an academic context, the term "nano-catalyst in homogeneous system" generally refers to a solution or nanoparticles suspension within a particular solvent. In the homogeneous nanocatalysis context, wherein the catalyst and reactants are in the same phase, it is imperative to address the issue of preventing catalyst aggregation during the design of a nanocatalyst intended for employment in a solution. NPs possess a unique property of agglomeration, which leads to their coalescence into larger particles, thereby compromising their advantageous large surface area and other associated benefits, unless effectively mitigated. The employment of polymer-based stabilization techniques to prevent the aggregation of nanoparticles is widely acknowledged as the most efficacious approach for stabilizing such particles in a solution.

The presence of elongated macromolecules precludes the possibility of nanoparticle agglomeration or coalescence, thereby impeding the formation of larger particles. Nevertheless, the process of stabilization leads to a decline in the comprehensive catalytic efficacy of the nano-catalyst, as it diminishes the accessibility of the NP surface for the molecules involved in the reaction. The retrieval of nano-catalysts from a system is a significant issue concerning homogeneous nanocatalysts. The elimination of nanoparticles from a solution is a widely acknowledged challenge, and the supplementary procedures required to achieve this objective may entirely nullify the streamlining of the process that was initially facilitated by the utilization of the catalyst.

The inability to recover homogeneous nanocatalysts presents a potential environmental hazard, given that most nanoparticles are resistant to incineration and the ecological implications of their accumulation remain largely uncertain. Furthermore, this situation poses a significant threat to the economic viability of the process, as evidenced by previous studies. The use of heterogeneous catalysis, wherein catalysts is in a different phase from a reactant, is widely regarded as a more ecologically sound approach to catalysis, primarily because of its higher recoverability. Normally, the heterogeneous catalyst is either the solid component or has been immobilized onto inert solid matrix. Currently, there is a growing interest within the scientific community to conduct research on the catalytic capabilities of different NPs support models. Various types of nanoparticles, such as ruthenium, copper, gold, platinum, rhodium, palladium, silver, iron, and nickel, have been utilized in recent times. The supporting materials employed for these nanoparticles encompass a wide range of substances, including silica, clays, zeolite, alumina, biowaste materials, and carbon fibers. The investigation of heterogeneous nanocatalysts has extended to the domain of nanostructured solids. Nanoporous materials can be synthesized through the process of solid material growth around a molecular template.

The implementation of conventional lithography techniques can facilitate the creation of nanoscale characteristics on the catalyst's surface. This process can potentially enhance the surface area and regulate the flow of reactants on the catalyst. The comprehension of how the elements and atomic-scale NPs structure yield optimal catalytic activity is a compelling scientific and technological obstacle in the utilization of nanoparticles as catalysts. The subsequent objective involves the synthesis of said particles with a high degree of precision in terms of their composition and structure. The potentials for futuristic development in the synthesis and characteristics of heterogeneous catalysis dependent on supported NPs is evident through the utilization of modern nanotechnology methods, as stated in reference. In their study, Hu, Liu, Ye, Ming, Xu, and Cao [3] investigated the catalytic features of copper NPs in the conversion of formaldehyde to hydrogen at ambient temperature. The authors also proposed a plausible reaction mechanism for this process.

The reduction of lindane (γ -hexachlorocyclohexane) in an aqueous environment was catalyzed by nanoscale Fe-Pd bimetallic particles, as reported by Pizarro, Gallardo, Gajardo, and Delgadillo [4]. The catalytic activities of Fe-Pd bimetallic model was enhanced for the lindane dechlorination through the presence of palladium on the nanoscale surface of iron particles. The process of dechlorination takes place through the mechanism of adsorption of chlorinated compounds, such as lindane, onto the surface of particles, as documented in reference. The surface of palladium functions as a hydrogen gas collector, which is generated through water molecules reduction in nanoscale iron presence, also known as the iron corrosion reaction. The reaction between nanoscale palladium and hydrogen gas results in the formation of either metal hydride or hydrogen radicals. Both exhibit high reactivity towards C-Cl bonds, resulting in the complete replacement of chlorine atoms in lindane to form cyclohexane.

The utilization of surface-functioning nano-magnetite-based NPs in catalysis, green chemistry, and pharmaceutically significant reactions was documented by Ganapathe, Mohamed, Mohamad Yunus, and Berhanuddin [5]. The nanoparticles serve as a mediator between homogeneous and heterogeneous catalysis. Metal nanocatalysts based on magnetite have been effectively utilized in organic synthesis for a range of significant reactions. **Table 1** presents a concise overview of a limited number of nano-catalysed reactions, showcasing the potentials of nano-catalysts in the organic synthesis field.

Table 1: Selected Nanocatalytic Organic Reactions Using Different NPs

2-hydroxychalcones diels Alder cycleaddition	Silver	1-pot benzofurans synthesis
1-pot caumarins synthesis via knoevenagel condensations	Zinc Oxide	Pyranopyrazole synthesis
Phenol synthesis, thiophenols anilines fro arylhalide	Copper	Aromatic acides and aldehydes synthesis
Hayama coupling reaction of benzylalide	Palladium	C-C coupling reaction
Synthesis of substituted pyridine	Calcium Oxide	1,4,6-trinit rophenol photodegradation
1,2,3-triazole synthesis	Gold	Epoxides deoxygenation

In the current era of nanotechnology, the size of various objects is continuously decreasing while their properties are being enhanced. Nano-sized catalysts are being utilized in numerous chemical processes, which are advantageous for human beings. Soltanali, Halladj, Rashidi, Hajjar, and Shafeghat [6] have compiled a comprehensive collection of literature pertaining to the utilization of nanocatalysts within recent years.

Carbon nanotubes

The physical and mechanical properties of nano-sized carbon materials (NCMs), predominantly carbon nanotubes (CNTs), have garnered significant interest in the scientific community. Carbon nanotubes (CNTs) have been utilized in various domains such as sources of field emission, Li ion secondary batteries, electric nano-conductors, fuel cells, electric double-layer capacitors, and molecular sieves. Furthermore, Carbon Nanotubes (CNTs) have been utilized for the purpose of hydrogen adsorption, as reported by Azab, Awadallah, Aboul-Enein, and Hassan [7], owing to their exceptional porosity,

low weight, stability, and cost-effectiveness. According to Zhang, Ye, Luo, and Sang [8], the tubular structure possessed by the subject in question is advantageous for the absorption of hydrogen. The potential of hydrogen as an energy carrier is widely recognized due to its high content of energy and environmentally-friendly properties. This has led to its consideration as model energy carriers, which could be extensively employed in the foreseeable future. The hydrogen storage capacity of carbon nanotubes (CNTs) is significantly influenced by their material properties, which are determined by the preparation methods, as stated in the literature by Vozniakovskii, Voznyakovskii, Kidalov, Ovchinnikov, and Kalashnikova [9]. Jahns, Ulrich, Schlereth, Reiff, Krupp, and Galetz [10] conducted research on a new method for preparing NCMs, used the process known as Metal Dusting (MD), which was established.

Furthermore, the potential utilization of the generated carbon nanotubes (CNTs) as a medium for hydrogen storage remains unexplored in scholarly works. The evaluation of the impact of acid-based post-treatment on micro-structures and hydrogen storage performances of carbon nanotubes (CNTs) is also conducted. The carbon nanotubes (CNTs) with multiple walls that were prepared at a temperature of 600°C exhibit a discharge of hydrogen with a capacity of approximately 57 mAh/g. This measurement was obtained through an electrochemical technique performed under standard temperature and pressure conditions. The study revealed that subjecting the as-prepared CNTs to post-acid treatments in nitric acid as a boiling solution for duration of 4 hours demonstrated to be an effective approach for the removal of metallic particles and amorphous carbon. Consequently, the capacity of the hydrogen discharge could be notably advanced to 104 milliamperes/hour/gram. Extending the etching duration results in a reduction of both the tubular structure and crystallinity of the carbon nanotubes (CNTs), leading to deterioration in the hydrogen storage efficacy. The findings of the experiment suggest that NCMs produced through MD have the potential to serve as viable options for hydrogen storage materials.

Water purification

Hydrogen is a recently introduced energy source that has garnered attention due to its numerous social, economic, and environmental advantages. One of its primary applications is in the chemical industry, where it is responsible for 40% of its overall usage. This highlights the significance of hydrogen gas and its substantial global demand in both present and future times. A high hydrogen quantity is used in various reduction procedures, including the metallic catalyst reduction utilized in hydrogenation and other chemical reactions, in addition to its application in hydrogenation reactions. Preparation techniques, which can generate catalysts in their respective metal forms without using hydrogen to change oxidic or different catalysts forms to their metal state, can be significant in limiting the usage of hydrogen.

According to Urazov and Sokolskiy Institute of Fuels, Catalysis and Electrochemistry, Almaty, and Kazakhstan [11], a novel electro-chemical deposition method was utilized to synthesize nano-metallic particles of silver onto carbon-based alumina support, as a means of sustaining a hydrogen economy. The aforementioned technique yields a silver-based catalyst that exhibits exceptional efficacy in regulating microorganisms present in aqueous solutions. It can be inferred from the evidence that catalysts supported by Ag are capable of being reused. The amalgamation of properties exhibited by carbon and Al₂O₃, such as decreased acidity levels, increased mechanical robustness and the presence of mesopores in CCA (carbon coating of alumina), and is advantageous in the development of a catalytic agent with exceptional activity, namely AgCCA.

The employment of visible light N-doped ZrO₂ and TiO₂ NPs was investigated by Kim, Kim, Chang, and Kim [12] to enhance the photodegradation efficiency of *Escherichia coli* bacteria and biofilm. The findings indicate that the photocatalytic performance of TiO₂-xNx varies depending on the nitrogen sources used, which can be attributed to the distinct binding N-dopants sites within certain metallic oxide matrix. Distinct kinetic patterns were observed during the bactericidal degradation of biofilm and *E. coli* bacteria in the absence of extracellular polymeric substance (EPS), highlighting the complexity of the abatement process. The bactericidal efficiency of most photocatalysts was significantly increased upon removal of soluble EPS from heterotrophic biofilm bacteria. The role of EPS in regulating bactericidal reaction kinetics has been identified as significant, as it competes with biofilm bacteria for ROS. The process of cellular substance degradation exhibits a comparatively prolonged duration in comparison to cell inactivation. However, the oxidation of carbohydrates and proteins displayed a similar pattern to that of bacterial eradication. The findings derived from the observations indicate that the composition of bacteria in a natural environment, such as biofilm, cannot be fully represented by all categories of organisms. The results indicate that nitrogen-doped titanium dioxide exhibits promise for utilization in the creation of substitute disinfectants for both medical and environmental purposes.

Bio diesel production

The heightened awareness of environmental preservation and the depletion of petroleum resources have led to a surge in research on biodiesel as a viable, sustainable fuel source. Biodiesel is characterized as the fatty acid monoalkyl esters. The utilization of biodiesel is increasingly prevalent in numerous nations, including Germany, France, Italy, the United States, Japan, and others. The conventional approach to producing biodiesel involves the homogeneous catalyzed transesterification reactions between alcohol and oil, as described by Ampairojanawong, Boripun, Ruankon, Suwanasri, and T. Kangsadan [13]. Despite its potential benefits, the homogeneous catalyst presents several limitations, including challenges in isolating the product, the need for significant amounts of water, and the potential for environmental pollution resulting from liquid waste. A recent development in the production of biodiesel involves the utilization of a "green"

approach utilizing heterogeneous catalysts, as reported in [14]. Although there has been extensive research on solid phase catalytic methods, their industrial applications remain restricted.

The aforementioned fact implies that additional investigation is imperative in order to address existing issues. According to Che, Louis, and Sojka [15], heterogeneous catalytic techniques are often impeded by mass transfer limitations, protracted reaction times, and suboptimal efficiency. Nanocatalysts possess notable characteristics such as elevated particular catalytic activity and surface area, which could potentially address the aforementioned issues. Recent studies have centered on them, as evidenced by the works of Ni et al. [16]. According to Wen, Wang, Lu, Hu, and Han [17], the utilization of KF/CaO solid base nanocatalyst in the production of biodiesel resulted in a yield exceeding 96%. The catalyst is effectively utilized for the conversion of oil with elevated acid value into biodiesel. The material exhibits porosity, characterized by particle dimensions ranging from 30 to 100 nanometers.

VII. CONCLUSION AND FUTURE RESEARCH

Nanocatalysis holds a pivotal position in academic and industrial research and development. The growing quantity of patents, technologies, and products in the market related to nanocatalysis serves as a clear indication of its industrial impact. The controlled preparation of metal nanoparticles with specific size and shape holds great potential for environmentally sustainable heterogeneous catalytic reactions. With an improved comprehension of the impact of size and shape of nanoparticles, as well as their interactions with stabilizing agents or support materials, researchers are currently making significant strides towards addressing contemporary environmental, social, and industrial challenges. This review offers an overview of nanocatalysis and aims to stimulate further research and development in this area. Catalysis is a longstanding area of chemical research that remains a highly active field due to its inherent merits. The advancement of nanoscience presents novel prospects in this field. The utilization of nanoparticles as a catalyst is not a recent development; however, contemporary advancements have augmented our capacity to visualize and evaluate their catalytic efficacy. The concept of nanocatalysis has been in existence since the early 1950s, a time in history when nanotechnology was not yet coined.

Following this report, the long-standing conventional notion regarding the chemical inertness of gold has been fundamentally altered, thereby unveiling a novel avenue for intriguing applications of nanoscale materials in the field of catalysis. Nanocatalysis presents a unique advantage by combining the advantages of both heterogeneous and homogeneous catalysis, namely, high catalytic activity (measured by the turnover frequency, TOF) and selectivity, similar to homogeneous catalysis, as well as the ability to recycle and separate the catalyst after the reaction is completed, thus resembling heterogeneous catalysis. The conventional heterogeneous catalyst systems exhibit two primary limitations in comparison to their homogeneous counterparts such as constrained surface areas, which is present to the reacting molecules, hence restricting their varied catalytic activities, and the consequent excessive consumption of costly catalyst materials. The utilization of catalytic materials at the nano-scale level has the potential to address the aforementioned issues through the amplification of the S/V. The aforementioned specifications serve as the foundation for the current state of nanocatalysis. Recent years have seen significant progress in the field of nanocatalysis, and current developments have created new opportunities in the scheming, synthesis, and formulation of catalytic materials that hold great importance for both industrial and biological applications. In addition to the aforementioned potential developments in the field of nanocatalysis, there will also be a focus on its implications for energy and environmental issues.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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There are no competing interests

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