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Utilization of Nanomaterials to Catalyze Chemical Reactions and Enhance Industrial Performance

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Annotation: Nanomaterials serve as effective catalysts for economically important chemical reactions and offer the potential to enhance industrial performance through sustainable and cost-efficient processes. They comprise metallic, metal oxide, carbon-based, and polymeric nanomaterials, each with unique structural features and properties that affect catalytic activity. Synthesis methods include top-down and bottom-up approaches, as well as green protocols, which influence the resulting nanomaterial characteristics. Comprehensive characterization employs electron microscopy, X-ray diffraction, and spectroscopic techniques to investigate morphology, crystallinity, elemental composition, and surface chemistry . Catalytic properties derive from large surface-to-volume ratios and abundant active sites that enhance interaction with reagents. Applications span organic synthesis, environmental remediation, and energy production, illustrating versatility across the chemical industry. Performance enhancements focus on higher conversion rates, lower costs, and improved sustainability. Despite various benefits, challenges remain concerning scalability, regulatory compliance, and safety, highlighting areas for future research and development.

1. Introduction to Nanomaterials

Nanomaterials are defined as materials that have at least one dimension that is smaller than one micrometer. The unique and remarkable properties of these materials arise as the size of the components approaches the nanoscale, where surface atoms play a dominant role over the interior atoms. This transformation leads to interesting characteristics that lead to various applications and innovations. Due to their high surface area and a significant percentage of surface atoms relative to their volume, nanomaterials are considered to be excellent catalysts in many chemical processes. The classification of nanomaterials includes four categories: zero-dimensional (0D), where all dimensions are smaller than 100 nm; one-dimensional (1D), which features two dimensions that are smaller than 100 nm; two-dimensional (2D), where only one dimension is smaller than 100 nm; and finally, three-dimensional (3D), which has no dimensions smaller than 100 nm. These diverse structures enable a wide array of applications in key areas such as catalysis, pollution remediation, 3D printing technology, and various industrial needs, all of which benefit substantially from these innovative materials. Specifically, nanomaterials act as catalysts to not only promote chemical reactions but also significantly enhance performance in industrial processes with greater efficiency and effectiveness. [1][2]

2. Types of Nanomaterials

Nanomaterials are nanoparticles with at least one dimension of the particle being less than 100 nm. Nanomaterials include particle sizes that range between 1 and 100 nm. Nanomaterials classification can be accomplished based on the constituent materials, phases of the nanomaterials, and shape of the nanomaterials. Based on the constituent nanomaterials, various types of nanomaterials can be classified as metallic, metal oxide, carbon-based, and polymeric nanomaterials.

Nanomaterials also can be classified based on the phases involved: monometallic, bi-metallic, tri-metallic, and core–shell type nanomaterials. Nanomaterial classification also can be achieved through the shape of the nanomaterial: nanorods, nanocubes, nanopolyhedra, nanospheres, core–shell nanoparticles, and nanosheets. Nanomaterial classification can be connected to the nanomaterial synthesis process to achieve the desired shapes.

2.1. Metallic Nanoparticles

Metallic nanoparticles are particularly appealing because of their extraordinary behavior. For instance, Au nanoparticles are catalytically inactive in bulk, but become very active at the nanoscale. Among transition metal-based nanocatalysts, Pt, Pd, Rh, and Ru have attracted widespread interest in various catalytic applications because of their unique electronic properties and their excellent catalytic activities. The extraordinary catalytic activities of these noble metal-based catalysts are also attributed to their high specific surface area and surface highly active atoms.

Platinum group metals (PGMs) are widely used in the production of soot-free emissions in automobile catalytic converters and catalytic methane combustion. Nevertheless, these catalysts are not economical and have poor thermal durability. To reduce the amount of PGMs and to improve the thermal stability in practical application, many studies have been conducted by adding other metals such as Cu, Ni, Co, and Fe into Pt nanoparticles. [3][4][5]

2.2. Metal Oxide Nanoparticles

In the pursuit of developing new catalytic materials with enhanced performance and safety, metal oxide nanoparticles emerge as prominent candidates due to their smart magnetic behavior and biocompatibility. Recent efforts have focused on preparing octahedral copper oxide (CuO) nanoparticles and evaluating their catalytic potential in diverse chemical and industrial reactions. The intrinsic versatility of CuO has also been demonstrated by exploring different nanomorphologies—nanowires, nanorods, and nanosheets—revealing variation in catalytic activity

The versatility of CuO extends across various nanomorphologies, each exhibiting distinct catalytic properties. The traditional top-down approach for CuO nanoparticle synthesis involves multiple steps, including reduction, stabilization, and nucleation with hydrazine, accompanied by the separation and removal of protective agents, such as cetyl trimethylammonium bromide (CTAB). By contrast, an octahedral shape can be achieved through a simplified one-step top-down synthesis. The stabilization of nanomaterials with polyvinylpyrrolidone (PVP) in aqueous medium ensures their applicability in industrial catalysis. The catalytic activity of PVP-supported CuO nanoparticles has been demonstrated across a spectrum of chemical transformations, including the reduction of 4-nitrophenol to 4-aminophenol, azo dye degradation, and oxidation of aromatic alcohols, underscoring their commercial value in industrial processes. [6][7][8]

2.3. Carbon-based Nanomaterials

Carbon-based nanomaterials are composed of carbon atoms and include carbon nanotubes, graphene, graphene oxide, fullerenes, and carbon dots, among others. Depending on the synthesis method, these nanomaterials can contain functional groups on their surfaces. They have been extensively utilized as catalysts in a wide array of organic reactions, including but not limited to hydrogenation of nitroaromatic compounds, synthesis of amines, the Heck reaction, the Suzuki–Miyaura coupling, the Sonogashira coupling, alkynes, and various oxidation reactions such as organocatalyzed epoxidation.

Carbon-based nanomaterials have proved efficient and selective in these reactions, significantly boosting the rate and yield of the products. Moreover, they have found applications in hydrogen production, energy storage, and environmental remediation. Their performance is markedly influenced by factors such as surface area, particle size, and morphology, alongside the active sites present on their surfaces.

2.4. Polymeric Nanomaterials

Polymeric nanomaterials, comprising several polymers assembled into nanoscale forms, bridge the gap between inorganic solid nanoparticles and liquid solutions and dispersions [9]. The solvents and polymers chosen define the dimensions, shape, and function of polymeric NMs [10]. Under precise synthesis conditions, polymeric materials can form distinct nanosized shapes—such as spheres, cages, or tubes—further reported as capsules, capsules, or pores that provide different functional architectures [11]. Carbohydrates, pseudo-polyamides and proteins, plastics, various fatty acids and soaps, and polymers such as polyanhydrides, poly(acrylic acid), and polyesters have all been employed as polymeric NMs. They have several advantages over other nanomaterials: notably their ease of synthesis, environmental compatibility, modest price, and good chemical modifiability, as well as the inherent structural adaptability imparted by the large variety of monomers available. In the last two decades, polymeric NMs have been utilized in the design of devices intended for various technological and healthcare applications, such as targeted drug delivery, biosensors and catalysis in a manner to boost industrial performance.

3. Synthesis Methods of Nanomaterials

Synthesis methods dictate the production of nanomaterials either by size reduction of bulk materials (top–down) or by aggregation of small atoms, ions or molecules (bottom–up). Top–down methods include mechanical milling, laser ablation, sputtering and electro-explosion of wire while bottom–up methods include chemical precipitation, sol–gel process, aerosol technique, dendrimer templating and many more [1]. Sol–gel and chemical precipitation methods produce nanopowders while dendrimer templating yields nanoparticles supported on surfaces [2]. Green synthesis means the use of an environmentally friendly, non-toxic medium, preferably water, to generate nanomaterials instead of highly reactive and toxic organic solvents. Non-toxic material as a reducing agent must generate yield of un-agglomerated nanoparticles between 10 and 100 nm to qualify as green synthesis.

3.1. Top-down Approaches

The top-down approach, commonly referred to as nucleation, involves the physical and chemical breakdown of bulk materials into their nanoscale counterparts [1]. Representative techniques typically involve milling, attrition, and thermal cracking, which can produce submicron particles on a rather routine basis. However, many of these procedures are difficult or altogether unsuccessful when it comes to scaling down to the desired nanometer-size regime. Nevertheless, a number of top-down strategies are capable of producing the targeted particle sizes, including electron, ion-, or laser (photo-) beam-lithography; etching with reactive ion or wet agents; and sputtering or successive rapid-melt growths. As a result of the miniaturization process, enhanced mechanical and electrical performances can arise along with a reduction in damage to the bulk material [2]. Bottom-up techniques are generally much easier to implement in the quest for nanomaterials and also offer more control over experimental parameters and, consequently, particle morphology and heterogeneity.

3.2. Bottom-up Approaches

Nanomaterials are constructed atom-by-atom or molecule-by-molecule in bottom-up approaches, which include chemical vapour deposition (CVD) and atomic layer deposition (ALD).

CVD deposits a material into a substrate from a gaseous state, and was first reported by Frederick Stanley in the 1960s. Later advances paved the way for the development of a wide range of industrial applications.

Another widely used bottom-up method for the synthesis of nanomaterials is ALD, a chemical deposition method which exploits sequential self-limiting surface reactions.

Nanomaterials synthesized by bottom-up methods tend to exhibit fewer defects and better uniformity than top-down approaches [1] [2]. These techniques require flexible control in order to customize the nanostructures for specific applications.

3.3. Green Synthesis Techniques

Green Synthesis constitutes an energy- and material-efficient approach that minimizes the use and generation of hazardous substances. This approach capitalizes on safer chemicals, renewable materials, atom-economical reactions, and alternative energy sources, often employing water as a benign medium with extracts from various renewable bioresources, such as plants, microorganisms, and biomass. Such a synthesis pathway has been employed to prepare, for instance, a wide spectrum of chemical compounds and nanomaterials with interesting catalytic, optical, and biomedical properties, including noble, transition, and post-transition metals and their derivatives in oxide, sulfide, selenide, and other chemical forms ([12]). The commonly used green reagents include plant extracts, biomolecules, saccharides, polyols, and hydrogen peroxide, while efficient energy sources typically exploited include microwave, ultrasonic, solar, UV, and γ-radiations (). Besides, genetically engineered microorganisms and enzymes—such as oxidoreductases and hydrolases—are often applied in catalytic syntheses as biomineralizing agents.

4. Characterization Techniques for Nanomaterials

Nanomaterial characterization is essential to ensure the expected enhanced properties derived from the synthesis method and prevent the presence of large particles that could degrade performance. The techniques employed provide information about structural, chemical, and physical aspects. Structural characterization determines crystallinity, phases, morphology, and size distribution, especially at the nanoscale. Chemical characterization identifies surface chemistry and impurities, both structurally incorporated and externally adsorbed. Physical characterization measures properties such as surface area and pore distribution, critical for catalytic efficiency [1].

The main instrumentation used includes electron microscopies, X-ray diffraction, and various spectroscopic techniques. Electron microscopy, encompassing scanning (SEM), transmission (TEM), and scanning transmission (STEM) modes, offers direct imaging of morphology and nanoscale features without complex data treatment, enabling localization of single particles where analytical methods also provide chemical composition and crystallinity insights. X-ray diffraction delivers information on crystallinity level, phase identification, particle size, and lattice parameters, frequently utilized after synthesis and during catalytic performance assessments to monitor catalyst transformations [13]. Spectroscopic methods, such as ultraviolet, visible, and infrared spectroscopies, characterize defects, chemical surface groups, particle size, and surface impregnation, and aid in monitoring reaction products.

4.1. Electron Microscopy

Electron microscopy is a powerful technique widely used to investigate the microstructure of nanomaterials. Transmission electron microscopy (TEM) can visualize their intrinsic structure, and high-resolution TEM (HRTEM) is capable of observing the lattice fringes of single crystals, revealing the exposed crystal plane and crystal defects.

TEM has been employed to investigate the morphology of various nanomaterials. Scanning electron microscopy (SEM) is an imaging method that analyzes the secondary electrons emitted by a material's surface when irradiated by a high-energy electron beam. Due to the shallow escape depth of secondary electrons, SEM images mainly represent the sample surface features. SEM has been used to characterize the morphology of different nanomaterials. Electron microscopy has also played an important role in the development of nanotechnology broadly. [14][15]

4.2. X-ray Diffraction

X-ray diffraction (XRD) serves as an indispensable technique for analyzing crystalline materials at the nanoscale with high structural integrity. The diffraction pattern arises from the constructive interference of monochromatic X-rays scattered by electrons within the crystal lattice, offering insight into atomic arrangements, unit cell parameters, and surface topology. This method enables precise determination of average crystallite size by correlating diffraction peak broadening with coherent scattering domains [16]. In studies of hydrocarbon pool species (HCP) formation, XRD reveals lattice expansion along the c axis; further buildup of coke-like aromatic species that block pores and induce deactivation becomes evident at advanced reaction stages. Spatial distribution of HCP formation, initiating mid-reactor and progressing toward the end point, can be tracked, and when complemented by extended X-ray absorption fine structure (EXAFS) and X-ray fluorescence, a comprehensive mechanistic understanding emerges. Surface diffraction is highly temperature-sensitive, complicating alignment procedures. Detector sensitivity diminishes at elevated photon energies, and achieving time resolution adequate for monitoring rapid reactions remains a technical hurdle. Developments in third-generation synchrotron sources markedly enhance XRD performance, with forthcoming advances in beam brilliance, coherence, detector sensitivity, and nano-focusing—driven in part by free electron laser technology—poised to extend capabilities still further.

4.3. Spectroscopic Methods

Spectroscopic methods such as UV-Vis, Fourier transform infrared (FTIR), X-ray photoelectron (XPS) and energy dispersive X-ray (EDX) spectroscopy provide detailed information on the optical absorption, functional groups, surface chemistry and elemental composition of nanomaterials. UV-Vis spectroscopy measures the interaction of ultraviolet or visible radiation with the nanomaterials and provides information about the electron distribution within the atomic or molecular orbitals. For example, absorption of light induces transitions of electrons in conduction band of TiO 2, which is monitored by UV-Vis spectroscopy. FTIR spectroscopy analyses the vibrations and rotations of chemical bonds and is performed by measuring the energy absorbed during interaction between infrared radiation and functional groups.

XPS is a nondestructive technique that monitors the elemental composition, chemical states and electronic states of the materials by measuring the photoelectrons emitted from surface. Energy dispersive X-ray spectroscopy is used to study the elemental composition of nanomaterials and to identify the impurities present in nanomaterials. However, orally-administered nanoparticles could react in vivo, during digestion and metabolism, via processes such as oxidation, conjugation or combination with proteins and therefore a more functional characterisation would helpful in predicting a nanoparticle-orientated enhanced industrial performance. It is also important to clearly define the product in terms of how it works, to be able to carry out relevant ‘‘omics’’ analysis, including proteomics, metabolomics or lipidomics. [17][18][19]

5. Catalytic Properties of Nanomaterials

Catalysing Chemical Reactions Nanomaterials exhibit greater catalytic activity than particles of larger sizes, a phenomenon generally ascribed to their larger surface area. The enhancement in catalytic behaviour is supported by the existence of more active sites such as corners and edges when the size scale is reduced to the nanometre range [1]. The catalytic properties of a material depend primarily on the amount and type of sites on the surface. The most abundant catalytic species usually present on these surfaces are metal ions that interact with the lone pairs of reactant molecules and make them more susceptible to transformation. For example, in the case of the formation of esters, the activation occurs through an interaction of the two metal ions with the carbonyl group of the acid reactant and the oxygen of the alcohol reagent. The catalytic activity is consequently closely linked to the presence of metal ions on the surface of the catalyst and the accessibility of these ions to the reactants. Nanomaterials of cobalt oxide are extremely active at room temperature in the total oxidation of methane; in contrast, all other cobalt oxide catalysts synthesized by conventional routes are active only above 400 C processes their bulk counterpart remains almost ineffective [20].

Industrial Catalytic Applications Nanomaterials find numerous catalytic applications in several fields such as the oil and gas industry, chemical industry, pharmaceutical chemistry, cosmetics, and high-tech materials. This is mostly due to their ability to display many redox sites, which very favourably affect reactions and processes. Pharmaceutical compounds containing the aromatic ring are produced from cooperative arylation by using metallic catalysts, various amination by metal catalysts with cobalt oxide (Co3O4) nanomaterials, cross-coupling with aryl iodides, and Buchwald–Hartwig amination [21]. Nanomaterials can also act as catalysts for the transformation of the biomass into high-value chemical products or feedstock for the production of fuels or commodity chemicals.

5.1. Surface Area and Catalytic Activity

Nanomaterials possess a higher surface area-to-volume ratio. Surface area effects govern the ability of nanomaterials to catalyze chemical reactions [22]. Heterogeneous catalysts are multidisperse populations of particles that contain a distribution of surface structures. This distribution is easily probed on nanometer-sized model catalysts. The use of nanocrystals has become common in the study of catalytic reactions. It has been shown that nanoscale catalysts mimic the behavior of the corresponding bulk single-crystal surfaces, which enables improvements in catalyst design and a better understanding of structure–function relationships. Size effects arise from the elemental composition of the catalyst, and coordination effects stem from the local atomic arrangement. The geometric arrangement of atoms within nanomaterials controls the selective formation of chemical products.

5.2. Active Sites and Mechanisms

Catalytic reactions depend on active sites and the surface area of catalysts, which increase with smaller particle sizes. Active sites on nanomaterials determine reaction pathways and influence selectivity and lifetime [1]. Modifying nanomaterials at an atomic level creates new material classes with unique catalytic properties, such as oxidants or hydrogen-generating catalysts. Introduction of active sites64including metal nanoparticles, heteroatoms (e.g., N, B, P), single metal atoms, defects, and surface atoms64alters catalytic behavior [23]. Most active sites function as Lewis acids or bases, and synergistic interactions between different sites affect catalytic performance. Active sites can also enhance overall reactivity within a composite system. Understanding and predicting the behavior of heterogeneous active sites remain challenging, requiring further investigation to exploit their potential fully.

6. Applications in Chemical Reactions

The success of nanomaterials in various catalytic reactions enables synthesis of diverse intermediates and end-use products. Nanomaterials catalyze reactions such as oxidation, hydrogenation, benzylation, Suzugi, Heck, Sonogashira, Seniey and cross-coupling reactions. These materials transform reactants into commercially valuable products efficiently and with excellent selectivity. Applications of nanomaterials in catalysis extend to environmental remediation, energy development, and industrial synthesis [1]. Plasmonics and photocatalysis generated by nanomaterials improve conversion of CO2 and water into hydrocarbons and other valuable chemicals. Nanomaterials can convert pollutants into non-toxic products via advanced oxidation processes, thereby providing solutions for environmental management.

6.1. Catalysis in Organic Chemistry

Nanotechnology is instrumental in achieving rapid, efficient, and sustainable pathways for chemical transformations and worldwide industrial development. The explosive development of the chemical industry greatly depends on sustainable and green industrial processes, and abundant effort has been devoted to attacking the problem [24]. In recent years, catalysis, crucially important to organic chemistry, has become a superior strategy to improve the above areas, with a tremendous range of applications across pharmaceuticals, biological activities, fuels, chemicals, and food sectors.

Catalysis is the principal driving force behind the development of the chemical industry that is of great significance to society, as it enables more efficient utilization of natural resources and substantial pollution reduction [1]. Metal nanomaterials have exhibited high catalytic activity and selectivity for specific chemical transformations such as oxidation, reduction, coupling, and electrochemical reactions, and have attracted increasing attention as a bridge between atoms and bulk materials with huge potential for applications in catalysis, biology, and medicine. Their catalytic properties can be adjusted through ultrasmall particle sizes, high surface-to-volume ratios, abundant active sites, and robust stability. Metal-based nanomaterials outperform conventional metal catalysts in terms of catalytic activity and selectivity, nanoparticle recyclability, and coupling with semiconductors or photothermal materials to undertake photocatalysis or photothermal catalysis.

6.2. Environmental Applications

Apart from their application in organic synthesis, nanomaterials of various types can catalyse environmental reactions. Water pollution and contamination by various organic and inorganic compounds are a growing threat to humankind and life on Earth. There are several methods to purify water, including biological treatment, chemical treatment, physical treatment and hybrid methods. Photocatalysis dominates such reactions due to the depletion of ozone and the greenhouse effect caused by other contaminants. Furthermore, non-conventional sources of energy are required that produce clean and green energy, such as hydrogen, to avoid global warming and climate change. Nanomaterials effectively catalyse environmental reactions because of their high surface area, low cost, ease of control and reusability.

The products of the water electrolysis process differ according to the electrolyte used: acid medium (H2+O2), base medium (H2+O2), and saline water (H2+Cl2). Water electrolysis is an intermittent way to produce hydrogen, as hydrogen can be used for storing energy from other sources. Hydrogen is a fuel having a very high energy value (2.8 times more than hydrocarbon fuels). State-of-the-art industrial catalysts for water separation are precious metals (Ir, Ru, Pt) and their alloys. However, the high cost and scarce availability of such catalysts are the main obstacles to large-scale hydrogen production via catalytic water splitting. Consequently, the exploration of nonprecious-metal bifunctional catalysts for overall water splitting to produce renewable and green hydrogen fuel has become imperative. [25][26]

6.3. Energy Production and Storage

The utilization of nanomaterials has attracted steady attention in the fields of energy production and storage due to their outstanding characteristics [27]. The energy sector employs nanostructured materials to produce fuel cells because of their distinctive properties stemming from confined dimensions. Stable structures with high surface-area-to-mass ratios selectively adsorb certain gases, allowing a larger gas fraction to participate in reactions. Nano-electrochemical energy systems frequently encounter challenges such as slow electrochemical kinetics, suboptimal gas and ion transport, chemical degradation, and mechanical failure, but development in this area continues. Obtaining viable alternative energy sources remains a crucial challenge. Nanomaterials can be employed individually or combined with nanostructured carbon correlates to improve catalyst performance; the material’s chemical activity relies on surface active sites, defining the degree of molecule adsorption [28]. Pt catalysts tend to agglomerate during continuous operation, making the search for active and stable alternatives essential. Nanostructured catalysts maximize platinum use, reducing loading and resulting in significant material enhancement. Advancing hydrocarbon reforming to produce hydrogen at elevated temperatures proves promising for cost reduction and leaf exploitation. Size-dependent catalytic mechanisms are vital to comprehending the rapid decrease in activity accompanying increasing nanoparticle radius from approximately 0.3 to 5 nm.

7. Enhancing Industrial Performance

Nanomaterials present considerable opportunities to improve many aspects of industrial processes. The majority of catalysts employed by industry are heterogeneous solids ejecting large amounts of powders that contaminate the product stream. Powder inhalation exposes workers to legitimate health risks that the industry must confront. The production of inevitable waste streams—catalyst fines—exacts a considerable cost in terms of the processes used to capture the solids prior to their release. One of the many solutions nanocatalysts offer involves reducing, if not eliminating, the problems associated with powders by use of suitable supports or immobilization strategies [29].

Nanostructures developing catalytic activity allow the use of fewer active centres and enable processes to be made much more efficient. The desired catalytic activity is achieved with a reduced number of active centres, so that one can operate with much lower quantities of the presumably much more expensive catalyst, a significant cost benefit. The reduced catalyst loading, combined with increases in process efficiency, can lead to small solvent volumes, lower energy costs, and reduced waste production [11].

Nanoreactors encapsulate the catalytic machinery, much like nano- or micro-vessels, with only small pores, or channels, allowing solvents, substrates and products to diffuse in and out. This means that the catalysts do not have direct contact with the reaction mixtures and are therefore not degraded by inappropriate interactions with solvent, reagents or products, a very serious problem at large scale. The reaction mechanism also requires that the catalysts do not have direct contact with each other—without sheltering, they sinter and agglomerate—another serious problem at scale.

A further advantage of nanoreactors lies in the possibility of carrying out many industrial processes in water, at room temperature, under air, with very high yields and selectivity. The nanoreactor can be almost instantly separated from the reaction mixture by a mere phase change when a stimulus-responsive shell is in place. This also allows catalyst reuse, a definite advantage when extremely expensive material is involved; it is also very straightforward to achieve product purification, an often overlooked, but usually very expensive, facet of industrial processes.

The economic and environmental benefits emanating from the ability to perform reactions in water, at room temperature, with very little work-up, coupled with dramatic increases in ‘catalyst stability’ can considerably reduce the industrial ‘footprint’. The catalyst also plays a pivotal role in the future of numerous industrial processes, and a strong growth in demand can be confidently foreseen. Nanomaterials display numerous benefits in a wide range of industrial processes.

7.1. Process Optimization

As demanded by the industry and the society, an independent perspective towards process optimization, other than only the basic aspects of catalytic reaction engineering, was tabled in relation to the exploitation of these nanomaterials and the approximate excerpts to the considered key-words, in particular for the purpose of enhancing efficiency and performance. To explore the full potential of these nanomaterials for an improved control on the chemistry of a deposition process and the development of new applications unprecedented to date, an example of addressing the challenges of hot filament CVD towards low-temperature synthesis is provided. Substitutional doping by co-depositing suitable impurities enables an application-specific adjustment of the properties of the synthesized layers. Retaining the function of these extraordinary nanomaterials also outside vacuum and at ambient conditions will drastically expand the diversity of application fields. The employment of such approaches has therefore the potential to trigger a second, nanomaterial-based innovation wave, to continue the ongoing industrial revolution and to substantially enhance the comfort in modernized societies worldwide. Cost remain the most important obstacle to the large-scale implementation of nanocatalysts and continue to come into play during every stage of the production process, from the synthesis step to the introduction of the catalyst in the reaction stream. Consequently, cost is the ultimate factor that conditions industrial exploitation and the principal reason for the low level of maturity of many promising nanocatalysts.

A pressing need exists for a technological leap towards a more efficient and sustainable production of nanomaterials with tailored properties, an indispensable premise for enabling widespread applications and securing a leading role in the ground-breaking nanotechnologies era. In this framework, an emerging technology is proposed based on the so-called Coaxial Pulse Ignition, a novel reactor design for the gas-phase synthesis of engineered nanomaterials [1]. According to this concept, the control and fine tuning of the synthesis conditions is achieved by modulating several parameters, among which the most important are the characteristics of the flow, the working pressure and temperature, the pulse frequency and discharge power and the gas composition [30]. Systems characterized by a high complexity open the possibility to tune a rich thermodynamic space to facilitate the prevention of defects formation and to realize synthesis conditions that would be unachievable otherwise.

The improvement of process ability and of the overall performances and efficiency is invariably at the top of the agenda of all applications based on these nanomaterials, as also corroborated by the approximate excerpts [11]. The specific solutions implemented to highlight different sites of opportunities where nanomaterials and their exploitation can enable increased efficiencies and performances to existing technologies, but also how novel technological paradigms can be empowered through the systematic introduction of nanomaterials and nanosystems.

7.2. Cost Reduction Strategies

Cost reduction strategies are a key benefit of nanomaterials, with a takeover of more conventional techniques in a variety of commercial industries. Nanomaterials increase the performance of the desired economic product and make them stable, easily recoverable, and reusable [1]. The catalytic effects of nanomaterials prevent the use of expensive and dangerous substances. Many procedures involve cumbersome, time-consuming synthesis or require expensive, heavy metal catalysts. For these reasons nanomaterials save money and serve as an alternative source.

During the manufacturing process there are still many methods to reduce the overall expense. Increased active areas accelerates the reaction rate, lower the reaction temperature, and shorten the reaction times. Therefore, lowering the operating temperature and reducing the use of more expensive raw materials can significantly reduce production costs [11]. A slower process will consume a larger amount of energy. Therefore, a faster reaction allows cost reduction strategies by reducing the use of power equipment.

Although accelerated reactions provide an economic advantage by lowering the amount of time through the costly process, this also applies remarkably to the recovery process. Compared with common catalysis techniques, the recovery of nanocatalysts employs a simpler method and greatly reduces the required energy consumption. Saving energy by the elimination the large-scale separation process further contributes to the lower utilities fees.

7.3. Sustainability and Eco-friendliness

Sustainability and eco-friendliness represent major drivers for the development of chemical production, fueling efforts to minimize industrial impacts on human health and the environment [11]. Since the concept of green chemistry was introduced to guide the chemical sector towards more benign processes, catalytic nanoreactors continue to gain interest, especially for multistep synthetic pathways requiring just one pot. Considerable support has accrued to nanostructures such as vesicles, micelles, dendrimers or nanogels, which facilitate organic reactions in water, enable cascade transformations and are readily recyclable. From an environmental perspective, water is a more acceptable solvent than common organic alternatives; the benefits are economic and environmental alike. Accordingly, its use as a reaction medium has the potential to curb waste and improve sustainability.

The acceleration of chemical processes therefore represents a central challenge for all industrial sectors worldwide [1]. Catalysis thus constitutes one of the central pillars of chemistry and serves as a key enabler for the synthesis of over 90% of all chemical products listed in the catalogue of the United States Pharmaceutical Industry. This includes compounds for pharmaceuticals, fuels, polymers, paints, food additives, flavors and perfumes. These matters relate directly to marketing and economic factors; they also affect the sustainability and eco-friendliness of product manufacturing. Since the genesis of catalytic nanoreactors, scientists have sought to develop alternative structures enabling greater efficiency and new functionalities at the nanoscale. Attention has consequently shifted towards catalysts that may be defined as biomimetic and capable of exploiting the benefits of enzymatic processes. Although a range of catalytic strategies exist, the main challenges encompass reaction efficiency, waste management, sustainability, and environmental impact.

8. Challenges in Nanomaterials Utilization

In spite of the remarkable effectiveness of nanomaterials in catalyzing reactions and enhancing industrial performance, theirreal-life deployment has been relatively limited, primarily due to challenges in large-scale production and inherent physical and chemical instability that can affect catalytic activity. While prospective hazardous effects have been scarcely established, the advent of the COVID-19 pandemic has significantly heightened the application of nanoparticles in protective measures. After more than two years of extensive administration and clinical trials, accumulating evidence suggests that these nanoparticles, within their current utilization scopes, do not introduce substantial safety or health concerns—this assessment encompasses nano-based catalytic applications, as well. Nonetheless, the incorporation of nanomaterials into catalytic processes engenders regulatory challenges.

The commercial landscape features a multitude of presently available catalytic product types, all fabricated using nanomaterials; however, the encapsulation of such entities by clients in terms of composition, production methods, and concentration is frequently inadequate. Sustainable development principles necessitate the evaluation of not only the constituents and reaction products but also the temporal evolution and degradation pathways of products, along with emissions during production, packaging, and utilization phases, as well as the practicability of recycling. Since fully assessing these aspects for every novel structure is often unattainable, special emphasis—aligned with European Commission methodologies—should be placed on upscaling concerns, including the availability of raw materials and scaling-related environmental and social impacts. [31][32]

8.1. Scalability Issues

Nanomaterials are materials with constituent particles in the nanoscale range (1–100 nm), which display novel/enhanced physical, chemical, and biological properties compared to bulk materials due to their large surface-area-to-volume ratio. Nanomaterials considered as catalysts in different chemical reactions and also to enhance the key parameters for the industrial sector are very essential for their scalability. The use of nanomaterials as catalysts can improve reaction rates and product selectivity, while reducing side reactions. They have led to a change in the way many chemical reactions are catalyzed. In addition, nanomaterials can also modify the key performance parameters for industrial production such as yields of different products, resources required, energy consumption, waste generation, cost of production, and overall sustainability. However, the complete utilization of the benefits associated with nanomaterials has not yet been realized. While a large body of research work has demonstrated the potential of nanomaterials in catalysis and in enhancing industrial production processes, the next step lies in translating these benefits to the commercial level in fields catering to the mass market.

A major challenge in scaling up the use of nanomaterials is the large-scale synthesis of well-defined nanostructures combining required shape, size, composition, crystallinity, and defects in a reproducible manner. The high level of control required often demands different synthesis conditions applied at each stage of nanomaterial formation, which are easier to implement at the laboratory scale than the industrial scale. [33][34][35]

8.2. Regulatory and Safety Concerns

Several regulators, including the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA), have recently issued guidance for industry considering the use of nanomaterials in applications such as food-packaging material, food antioxidants, or mineral food supplements. Such regulations are intended to maintain the highest levels of safety and transparency for the public, triggered by the increasing use of synthetic nanomaterials across various industrial applications and concerns about the toxicity of nanomaterials. Due to the novel and unknown nature of nanomaterials, these regulations are important but also challenging because they provide testing guidelines for substances with new and unknown properties. Overall, very few nanoparticles have been approved for use in food and food-related industries, including Ag and Au nanoparticles in packing materials, and TiO_2, SiO_2, and ZnO nanoparticles as antimicrobial or food additives. Even if these materials are regarded as safe, questions remain about whether they may have long-term effects on humans (e.g., allergies or sensitization) and the environment, further hampering their commercial successes.

These concerns have led to the exploration of greener and more natural approaches. One alternative solution is the use of extracts of plants from which the biogenic synthesis of nanoparticles is induced. For example, the kiwifruit extract has been proposed for the formation of Ag nanoparticles. The natural and mild reducing agents from the fruit were able to convert Ag ions to metallic Ag in 24 h, resulting in nucleation and growth of the nanoparticles. However, these natural precursors in biogenic synthesis systems may have batch-to-batch inconsistencies and may not be suitable for industrial scales because of their high cost. [36][37][38]

9. Future Perspectives

Nanomaterials significantly enhance the performance of chemical processes due to their large surface-to-volume and surface-to-mass ratios. Consequently, nanomaterials have attracted substantial attention, and numerous approaches have been developed to deploy nanomaterials for catalysis and industrial applications. Nevertheless, many challenges remain in realizing the full potential of nanomaterials across diverse industrial sectors. Ongoing investigations into smart chemical nanocatalysts, innovative catalytic systems, and novel engineering processes aim to overcome these hurdles. As the field continues to advance rapidly, research holds high probability for fomenting sustainable innovations and potentially creating new markets, opportunities, and competitive advantages.

9.1. Innovations in Nanotechnology

Innovations in Nanotechnology

The 200-year-old phenomenon of catalysis underpins the production of over 90% of all manufactured products, from solvents and paints to water treatment agents and fuels [1]. Catalytic processes are conventionally divided into homogeneous and heterogeneous systems, the former involving reactants and catalysts in the same phase and the latter in different phases. The well-documented advantages of heterogeneous systems have driven the search for catalytic materials that combine the activity of homogeneous catalysts with heterogeneous-like operational benefits. Nanocatalysts fulfill these requirements by both providing accessible active sites and ensuring stability, reusability, and ease of recovery. This suite of features accounts for the recent explosion of academic interest in nanomaterials and their catalytic applications.

Nanotechnology covers research and innovation aimed at deploying materials with at least one dimension in the 1–100-nm size range. At that scale the optical, electrical, magnetic, and chemical properties of materials differ radically from their bulk counterparts, greatly widening the spectrum of practical applications. For example, Co3O4 becomes catalytically active at room temperature when reduced to nanometer scale, in sharp contrast to the bulk metal oxide, which exhibits none of these properties. Nanoreactors, including polymersomes, micelles, dendrimers, and nanogels, possess high active surface area relative to their volume combined with good dispersion and efficient catalyst protection. Especially in water and at room temperature, these features translate into high yields and selectivities [11]. The capacity for easy separation from reaction mixtures facilitates catalyst reuse and reduces consumption of organic solvents, which benefits both the economy and the environment. Despite these advantages, commercial adoption remains problematic because manufacturing nanoreactors competes with established, large-scale processes. The challenge of scalability affects many nanomaterial synthesis routes, while reproducibility and the high cost of some components further complicate industrial deployment. Lastly, the wide-reaching societal consequences of nanostructures remain unclear owing to persistent ambiguities in toxicity and risk evaluations [39]. Advancements in one-pot multi-step conversions and continuous flow processing could allow selective production of chemicals inaccessible by traditional routes, reduce waste quantity, increase the lifetime of fine chemicals, and enable conversion of low-value materials, all of which contribute to sustainability from a chemical perspective.

9.2. Potential Market Growth

The market for nanomaterials is expected to expand with increasing opportunities and growth potential across multiple industries. Catalysis is the fundamental chemical process for manufacturing more than 90% of the industrial products used by consumers, particularly pharmaceuticals, fibers, fuels, detergents, and polymers [1]. Energy demand continues to rise, links strongly to the availability of chemical products, and is connected to the efficiency of their production, significantly improving industrial performance and global living standards. Catalysts accelerate chemical reactions by reducing their activation energy, reducing the amount of energy needed to drive the process and the quantity of undesired by-products generated. They also provide other benefits, such as improved selectivity, lower reaction temperatures, increased yields, safer operating conditions, and enhanced purity of products. Since the catalytic steps usually occur in the heart of the process, catalysis is a key enabler of sustainability in the design and enhancement of industrial processes. Over the past decades, catalysis has become a vital technology for addressing many of the world’s most pressing environmental problems, finding applications in exhaust gas purification, automotive combustion processes, and water treatment.

10. Conclusion

Nanomaterials, characterized by their sub-100 nm dimensions, concentrate surface atoms on the exterior, thereby altering their physical and chemical properties, aspect ratio, quenching rate, and surface free energy. These unique attributes have been extensively exploited. Nanotechnology—a field encompassing nanomaterials, nanoscience, nano-synthesis, and nano-applications—has been leveraged to develop methods that improve catalysis, reduce operational times for chemical reactions, decrease manufacturing costs, eliminate hazardous byproducts, and enhance overall industrial performance. For instance, employing nanomaterials in catalytic applications aids industries in reducing carbon footprints and achieving sustainable production targets.

Nanomaterials encompass various classes, including metallic and metal-oxide-based types alongside polymeric forms such as graphene and carbon nanotubes. Due to the distinctive chemical nature of these materials, they are employed to catalyze a broad spectrum of chemical reactions and are pivotal in improving the performance of diverse industrial sectors. Their utilization contributes to the development of a sustainable and safe environment, underscoring the integral role of nano-catalysis in modern industry.

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