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Nano-Chemistry in Drug Delivery, Catalysis, and Environmental Remediation: Progress and Future Perspectives

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ABSTRACT

Nano-chemistry has evolved as a powerful and unifying discipline that enables precise control over material properties at the nanoscale, leading to transformative advances across drug delivery, catalysis, and environmental remediation. This review critically examines the fundamental principles of nano-chemistry, including size-dependent physicochemical behavior, surface functionalization, self-assembly, and quantum effects, and illustrates how these concepts underpin diverse applications. Nano-enabled drug delivery systems demonstrate improved solubility, stability, bioavailability, and safety, while nano-catalysts offer enhanced activity, selectivity, and sustainability in green chemical processes and pharmaceutical manufacturing. In environmental remediation, nanomaterials provide efficient strategies for pollutant adsorption, photocatalytic degradation, and water treatment. A comparative cross-domain analysis highlights common nano-chemical principles alongside domain-specific design requirements, toxicity concerns, and regulatory challenges. Finally, emerging trends such as AI-assisted material design, biodegradable nanomaterials, personalized nanomedicine, and circular-economy-driven remediation are discussed, emphasizing future research directions and translational opportunities for sustainable and responsible nano-chemistry. Dept. of Pharmaceutics.

1. INTRODUCTION:

Nanochemistry has emerged over the past three decades as a distinct and transformative discipline within the chemical sciences, driven by the ability to design, synthesize, characterize, and manipulate matter at the nanometer scale (1–100 nm)[1]. Initially rooted in colloid chemistry and surface science, nanochemistry evolved rapidly with advances in physical chemistry, solid-state chemistry, and analytical instrumentation, particularly electron microscopy and spectroscopic techniques[2,3]. Early investigations focused on size-dependent properties of metal clusters and semiconductor nanoparticles; however, the scope of nanochemistry has expanded significantly to encompass functional nanomaterials, hybrid nanostructures, and application-driven nanosystems[4]. Today, nanochemistry plays a central role in addressing challenges across healthcare, energy, catalysis, and environmental sustainability[5,6].

A defining feature of nanochemistry is its inherently interdisciplinary nature. The field represents a convergence of traditional chemistry with materials science, pharmaceutics, and environmental science, enabling the rational design of nanoscale systems with tailored physicochemical and functional properties[7]. From a materials science perspective, nanochemistry provides synthetic control over composition, morphology, crystallinity, and surface chemistry, which directly govern mechanical, optical, electronic, and catalytic behaviors[8]. In pharmaceutics, nanochemical principles underpin the development of advanced drug delivery systems that improve solubility, stability, bioavailability, and targeted delivery of therapeutic agents[9]. Simultaneously, environmental science benefits from nanochemistry through the creation of efficient adsorbents, photocatalysts, and reactive nanomaterials for pollutant detection, degradation, and remediation[10-12]. The seamless integration of these domains reflects the versatility of nanochemistry as a unifying platform for both fundamental and applied research.

The transformative impact of nanochemistry arises primarily from nanoscale phenomena that are absent or negligible in bulk materials. One of the most significant factors is the dramatically increased surface area-to-volume ratio exhibited by nanomaterials. At the nanoscale, a substantial fraction of atoms resides on or near the surface, resulting in enhanced surface reactivity, adsorption capacity, and interfacial interactions[13]. This property is particularly advantageous in catalysis, where high surface availability of active sites leads to improved catalytic efficiency and selectivity, and in environmental remediation, where rapid adsorption and degradation of contaminants are required[14,15]. In drug delivery, increased surface area facilitates higher drug loading and enables surface functionalization for targeted and controlled release[16].

In addition to surface effects, quantum confinement plays a critical role in dictating the behavior of nanoscale materials. When particle dimensions approach the de Broglie wavelength of electrons, discrete energy levels emerge, leading to size-dependent optical, electronic, and magnetic properties[17]. These quantum effects have been extensively exploited in semiconductor nanocrystals, metal nanoparticles, and carbon-based nanostructures, enabling applications ranging from bioimaging and sensing to photocatalysis and energy conversion[18,19]. Tunable reactivity is another hallmark of nanochemistry, as subtle variations in size, shape, composition, or surface ligands can significantly alter reaction pathways and biological interactions[20]. Such tunability provides unprecedented control over material performance, allowing nanochemical systems to be optimized for specific therapeutic, catalytic, or environmental functions.

Given these unique attributes, nanochemistry has become a cornerstone for innovation in three strategically important application areas: drug delivery, catalysis, and environmental remediation[21]. In pharmaceutical sciences, nanocarriers such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, and inorganic nanostructures have demonstrated the ability to overcome limitations associated with conventional dosage forms, including poor solubility, nonspecific distribution, and systemic toxicity[22,23]. In catalysis, nanostructured catalysts offer superior activity, stability, and recyclability compared to their bulk counterparts, contributing to greener and more energy-efficient chemical transformations[24]. In environmental remediation, nanomaterials enable advanced treatment strategies for water, air, and soil pollution through adsorption, photocatalytic degradation, and redox-based processes[25-27].

Despite extensive literature in each of these individual domains, reviews often address drug delivery, catalysis, and environmental remediation in isolation[28]. However, these application areas are fundamentally linked by common nanochemical principles, including surface engineering, interfacial phenomena, structure–property relationships, and reaction kinetics at the nanoscale[29]. Integrating these fields within a single comprehensive review provides a holistic understanding of how nanochemistry-driven design strategies can be translated across disciplines. Such an integrated perspective not only highlights shared challenges—such as scalability, stability, toxicity, and environmental impact—but also reveals opportunities for cross-fertilization of ideas, for example, adapting catalytic nanomaterials for therapeutic use or employing drug-delivery-inspired surface functionalization in environmental systems[30].

The rationale for integrating drug delivery, catalysis, and environmental remediation within one review is further strengthened by the growing emphasis on sustainability and translational impact. Modern chemical research increasingly demands solutions that are efficient, environmentally benign, and socially relevant. Nanochemistry, by virtue of its tunable and multifunctional nature, offers pathways to develop materials that simultaneously address human health, industrial efficiency, and environmental protection[31]. A unified discussion of these application areas allows for critical comparison of design strategies, performance metrics, and regulatory considerations, thereby facilitating the rational development of next-generation nanochemical systems.

2. Fundamentals of Nano-Chemistry:

Nanochemistry is fundamentally concerned with understanding and exploiting chemical phenomena that emerge when matter is structured at dimensions typically below 100 nm. At this length scale, classical chemical rules based on bulk behavior are often insufficient to explain observed properties, as size reduction introduces new surface, electronic, and interfacial effects. The fundamentals of nano-chemistry therefore lie at the intersection of physical chemistry, surface science, and materials chemistry, providing a theoretical and practical framework for designing nanomaterials with predictable structure–property–function relationships[32].

2.2 Size-Dependent Physicochemical Properties:

One of the most defining principles of nano-chemistry is the strong dependence of physicochemical properties on particle size. As materials transition from bulk to nanoscale dimensions, dramatic changes are observed in optical absorption, electrical conductivity, magnetic behavior, melting point, and chemical reactivity[33]. These effects arise primarily because a large fraction of atoms in nanoparticles are located at or near the surface, leading to reduced coordination numbers and altered electronic structures.

Metallic nanoparticles exhibit size-dependent plasmonic properties, while semiconductor nanoparticles show tunable band gaps that directly influence their optical and photocatalytic performance[34].

In pharmaceutical applications, nanosizing improves dissolution rate and apparent solubility of poorly water-soluble drugs, thereby enhancing bioavailability and therapeutic efficacy[35]. In environmental chemistry, nanoscale adsorbents demonstrate superior contaminant removal efficiencies[36].

2.3 Surface Chemistry and Functionalization:

Surface chemistry is a central pillar of nano-chemistry, as surface atoms dominate the chemical behavior of nanomaterials. Nanoparticles possess high surface energies, making them inherently reactive and prone to aggregation unless stabilized through surface modification[37]. Surface functionalization involves the deliberate attachment of organic ligands, polymers, biomolecules, or inorganic shells to control colloidal stability and interfacial interactions.

In drug delivery, surface functionalization enables targeted delivery and controlled release. In catalysis, surface modification influences selectivity and turnover frequency. Environmental applications rely on surface-engineered nanomaterials to enhance selectivity toward pollutants[38,39].

2.4 Self-Assembly and Supramolecular Interactions:

Self-assembly is a fundamental nano-chemical process by which molecular or nanoscale building blocks spontaneously organize through non-covalent interactions[40]. This bottom-up approach allows the construction of complex nanostructures with hierarchical organization.

Supramolecular chemistry enables the formation of micelles, vesicles, nanofibers, and layered architectures with precise control over morphology[41]. In catalysis, self-assembled nanostructures improve efficiency and recyclability. Environmental systems exploit self-assembly to fabricate porous hybrid materials[42].

2.5 Quantum Confinement and Catalytic Hotspots:

Quantum confinement becomes significant when particle dimensions approach electronic length scales, leading to discrete energy levels and size-dependent optical and redox properties. Quantum dots and metal nanoclusters show tunable photoluminescence useful in sensing and photocatalysis[43].

In heterogeneous catalysis, nanoscale materials exhibit localized regions of enhanced activity known as catalytic hotspots, arising from surface defects and metal–support interfaces. These hotspots are central to nanocatalyst performance and green chemical transformations[44,45].

3. Nano-Chemistry in Drug Delivery Systems:

Nano-chemistry has profoundly reshaped modern drug delivery by enabling the rational design of carrier systems at the molecular and supramolecular levels. Conventional dosage forms often suffer from poor aqueous solubility, rapid degradation, nonspecific distribution, and dose-limiting toxicity. By contrast, nano-enabled drug delivery systems exploit size-dependent effects, surface chemistry, and controlled self-assembly to overcome these limitations and enhance therapeutic performance. From a nano-chemical perspective, drug delivery systems are no longer passive carriers but engineered nanosystems whose composition, architecture, and surface functionality are precisely tuned to achieve desired pharmacokinetic and pharmacodynamic outcomes[46,47].

3.2 Polymeric, Lipid, Inorganic, and Hybrid Nanocarriers:

Polymeric nanocarriers represent one of the most extensively studied classes of nano-enabled drug delivery systems. These include polymeric nanoparticles, nanospheres, nanocapsules, and polymeric micelles formed from biodegradable polymers such as poly (lactic-co-glycolic acid), polycaprolactone, and polyethylene glycol. Nano-chemistry governs polymer chain arrangement, hydrophobic–hydrophilic balance, and self-assembly behavior, which collectively determine drug encapsulation efficiency and release kinetics. Polymeric systems offer excellent versatility, tunable degradation profiles, and compatibility with a wide range of therapeutic agents[48].

Lipid-based nanocarriers, including liposomes, solid lipid nanoparticles, and nanostructured lipid carriers, rely on amphiphilic self-assembly principles central to nano-chemistry[49]. These systems mimic biological membranes, enabling efficient encapsulation of both hydrophilic and lipophilic drugs while improving biocompatibility and reducing immunogenicity. The physicochemical properties of lipid nanocarriers, such as phase behavior and surface charge, are strongly influenced by nanoscale organization and interfacial chemistry.

Inorganic nanocarriers, such as silica nanoparticles, gold nanoparticles, iron oxide nanoparticles, and quantum dots, offer unique advantages including high structural stability, imaging capability, and surface functionalization flexibility(50). Their rigid frameworks and well-defined surfaces allow precise control over drug attachment and release, although concerns related to long-term biocompatibility and accumulation remain critical. Hybrid nanocarriers combine polymeric, lipid, and inorganic components to integrate the advantages of multiple systems, representing an important nano-chemical strategy for multifunctional drug delivery[51].

3.3 Drug Loading Strategies and Controlled Release Mechanisms:

Drug loading in nano-carriers is governed by nano-chemical interactions such as hydrophobic forces, electrostatic attraction, hydrogen bonding, and covalent conjugation. Physical encapsulation within polymeric or lipid matrices remains the most common approach, offering simplicity and high loading for hydrophobic drugs. Alternatively, surface adsorption and chemical conjugation enable precise control over drug density and release behavior, particularly for macromolecules and biologics.

Controlled release is a defining advantage of nano-enabled drug delivery systems. Release mechanisms are dictated by carrier degradation, diffusion through the nano-matrix, or cleavage of stimuli-sensitive linkages. Nano-chemical design allows modulation of these mechanisms by adjusting particle size, crystallinity, crosslinking density, and surface chemistry. Such control minimizes burst release, maintains therapeutic concentrations over extended periods, and reduces dosing frequency[52].

3.4 Targeting Approaches: Passive, Active, and Stimuli-Responsive:

Targeting strategies are central to improving the specificity and safety of nano-drug delivery systems. Passive targeting exploits physiological phenomena such as the enhanced permeability and retention effect, enabling preferential accumulation of nanosized carriers in diseased tissues[53]. This approach is inherently size- and surface-dependent, highlighting the importance of nano-chemical control over particle dimensions and surface charge.

Active targeting involves surface functionalization of nanocarriers with ligands such as antibodies, peptides, sugars, or small molecules that recognize specific cellular receptors(54). Nano-chemistry enables stable ligand attachment while preserving biological activity and carrier integrity. Stimuli-responsive systems represent an advanced targeting paradigm, where drug release is triggered by internal stimuli (pH, enzymes, redox potential) or external stimuli (temperature, light, magnetic fields). These systems rely on smart nano-chemical linkages and phase transitions to achieve site-specific and on-demand drug release[55].

3.5 Nano-Chemistry Driven Improvements:

One of the most significant contributions of nano-chemistry to drug delivery is the improvement of solubility and dissolution rate of poorly water-soluble drugs through nanosizing and encapsulation[56]. Enhanced physical and chemical stability is achieved by protecting drugs from hydrolysis, oxidation, and enzymatic degradation within nano-carrier matrices. These effects collectively translate into improved bioavailability and reduced inter-patient variability[57].

Safety enhancement is another critical outcome of nano-chemical design. Targeted delivery and controlled release reduce off-target exposure and systemic toxicity, while surface modification with biocompatible polymers minimizes immune recognition and clearance. However, nano-chemistry also necessitates careful evaluation of carrier fate, degradation products, and long-term toxicity, underscoring the need for rational and responsible nanosystem design[58].

4. Nano-Chemistry in Catalysis:

Nano-chemistry has fundamentally transformed catalysis by enabling precise control over catalyst composition, size, morphology, and surface structure at the atomic and molecular levels. Compared to conventional bulk catalysts, nano-catalysts exhibit superior activity, selectivity, and efficiency due to enhanced surface-to-volume ratios, quantum size effects, and the presence of catalytically active surface sites. These attributes have positioned nano-chemistry as a key enabler of sustainable catalytic processes in green chemistry, energy conversion, and pharmaceutical manufacturing[59,60].

4.1 Metal and Metal-Oxide Nanoparticles:

Metal and metal-oxide nanoparticles constitute the most widely investigated class of nano-catalysts. Noble metals such as gold, platinum, palladium, and silver display remarkable catalytic activity at the nanoscale, even for reactions where their bulk counterparts are inactive. Transition metal oxides, including TiO_2, ZnO, and Fe_3O_4, are extensively used in oxidation, photocatalytic, and redox reactions due to their tunable electronic structures and surface reactivity.

Nano-chemical synthesis routes such as sol–gel processing, co-precipitation, and hydrothermal methods enable fine control over particle size and dispersion, directly influencing catalytic performance. The ability to tailor metal–support interactions at the nanoscale further enhances catalyst stability and reusability, which are critical for industrial applications[61].

4.2 Nano-Enzymes and Single-Atom Catalysts:

Recent advances in nano-chemistry have led to the development of nano-enzymes (nanozymes) and single-atom catalysts, representing a new frontier in catalysis. Nanozymes are nanomaterials that mimic natural enzyme activity while offering superior stability, lower cost, and broader operational conditions. These systems have shown promise in environmental remediation and biomedical applications, particularly where harsh conditions limit the use of natural enzymes[62].

Single-atom catalysts, in which isolated metal atoms are dispersed on suitable supports, maximize atom utilization and exhibit unique catalytic pathways distinct from nanoparticle-based systems. Nano-chemical stabilization of single atoms through coordination environments and defect engineering is crucial for preventing aggregation and maintaining catalytic efficiency. These catalysts are increasingly explored for selective organic transformations and pharmaceutical intermediate synthesis[63].

4.3 Role of Morphology, Crystal Facets, and Surface Defects:

Catalytic performance at the nanoscale is strongly influenced by particle morphology, exposed crystal facets, and surface defects. Different shapes such as cubes, rods, plates, and octahedra expose distinct crystallographic planes, each possessing characteristic atomic arrangements and reactivity[64]. Nano-chemistry enables selective facet exposure, thereby tuning adsorption energies and reaction kinetics.

Surface defects, including vacancies, steps, and edges, act as catalytic hotspots that facilitate bond activation and electron transfer. Defect engineering through controlled synthesis or post-treatment has emerged as an effective strategy to enhance catalytic activity without increasing catalyst loading. Understanding these structure–activity relationships is central to rational nano-catalyst design[65].

4.4 Applications in Green Chemistry, Energy, and Pharmaceuticals:

Nano-catalysts play a pivotal role in green chemistry by enabling reactions under milder conditions, reducing waste generation, and improving atom economy. In energy-related applications, nano-catalysts are integral to fuel cells, water splitting, and CO_2 reduction processes, where high efficiency and durability are essential[66].

In pharmaceutical chemistry, nano-catalysts facilitate selective hydrogenation, oxidation, and coupling reactions used in the synthesis of active pharmaceutical ingredients and intermediates. Their high selectivity and recyclability contribute to cleaner and more cost-effective manufacturing processes. Collectively, these applications underscore the broad impact of nano-chemistry in advancing sustainable and high-performance catalytic systems[67].

5. Nano-Chemistry in Environmental Remediation:

Nano-chemistry has emerged as a powerful tool for addressing complex environmental pollution challenges by enabling the design of materials with high reactivity, selectivity, and efficiency at the nanoscale. Conventional remediation techniques often suffer from low removal efficiency, high energy demand, and secondary pollution. Nano-chemical approaches overcome these limitations by exploiting large surface areas, tunable surface chemistry, and catalytic activity, particularly in water and wastewater treatment applications[68].

5.1 Adsorption of Heavy Metals and Organic Pollutants:

Adsorption is one of the most widely applied nano-chemical strategies for environmental remediation. Nanomaterials such as carbon nanotubes, graphene oxide, metal oxides, and polymer-based nanocomposites exhibit exceptional adsorption capacity toward heavy metals (e.g., Pb^{2+}, Cd^{2+}, Hg^{2+}) and organic pollutants due to their high surface area and abundance of functional groups. Surface functionalization further enhances selectivity by introducing specific binding sites for targeted contaminants[69].

Nano-chemistry enables precise control over pore size, surface charge, and chemical functionality, allowing rapid and efficient pollutant capture even at low concentrations[70]. These properties make nano-adsorbents particularly attractive for treating industrial effluents and contaminated groundwater.

5.2 Photocatalytic Degradation of Dyes and Pharmaceuticals:

Photocatalysis represents a major nano-chemical approach for the degradation of persistent organic pollutants, including dyes, pesticides, and pharmaceutical residues. Semiconductor nanoparticles such as TiO_2, ZnO, and doped metal oxides generate reactive oxygen species under light irradiation, leading to mineralization of complex contaminants. Nanoscale engineering enhances photocatalytic efficiency by improving light absorption, charge separation, and surface reaction kinetics[71].

Recent nano-chemical strategies focus on heterostructures and surface-modified photocatalysts to extend activity into the visible region and reduce recombination losses. These advancements are particularly relevant for pharmaceutical pollutants, which are increasingly detected in water bodies and resist conventional treatment methods.

5.3 Nano-Membranes and Magnetic Nanoparticles for Water Treatment:

Nano-membranes incorporating nanofillers such as metal oxides, carbon nanomaterials, or polymeric nanoparticles offer improved permeability, selectivity, and fouling resistance compared to conventional membranes. Nano-chemical modification of membrane surfaces enables controlled hydrophilicity and antimicrobial properties, enhancing long-term performance in water purification systems[72].

Magnetic nanoparticles, particularly iron oxide–based systems, are widely used for water treatment due to their high adsorption capacity and ease of separation using external magnetic fields. Nano-chemistry facilitates surface coating and functionalization of magnetic nanoparticles, allowing repeated use with minimal secondary contamination[73].

5.4 Environmental Fate, Toxicity, and Sustainability Concerns:

Despite their effectiveness, the environmental application of nanomaterials raises concerns regarding toxicity, persistence, and ecological impact. Nano-chemical properties that enhance reactivity may also induce oxidative stress or bioaccumulation in living systems. Understanding the environmental fate, transformation, and degradation of nanomaterials is therefore essential for responsible deployment[74].

Sustainable nano-chemistry emphasizes green synthesis routes, biodegradable materials, and life-cycle assessment to minimize environmental risks. Integrating performance evaluation with toxicity and sustainability studies is critical for translating nano-remediation technologies from laboratory to real-world applications[75].

6. Comparative Cross-Domain Analysis:

Nano-chemistry provides a common scientific foundation for applications in drug delivery, catalysis, and environmental remediation. Although these domains differ in objectives and constraints, they rely on shared nanoscale principles governing material behavior, interfacial interactions, and structure–property relationships. A comparative analysis highlights both the unifying concepts and the domain-specific design requirements that shape nano-chemical system development[76].

6.1 Drug Delivery vs. Catalysis vs. Environmental Remediation:

In drug delivery, nano-chemical systems are designed to interact with biological environments, requiring precise control over particle size, surface chemistry, and biocompatibility to achieve safe and effective therapeutic outcomes. In contrast, catalytic applications prioritize high activity, selectivity, and stability under often harsh reaction conditions, where biological compatibility is not a primary concern. Environmental remediation lies between these extremes, demanding high reactivity and robustness while minimizing ecological toxicity and secondary pollution.

Despite these differences, all three domains exploit nanoscale features such as high surface area and tunable reactivity. However, acceptable material lifetimes, regeneration strategies, and regulatory expectations vary significantly, influencing nano-chemical design choices across applications[77].

6.2 Common Nano-Chemical Principles Across Domains:

Several nano-chemical principles are universally applicable across drug delivery, catalysis, and environmental remediation. These include size-dependent physicochemical properties, surface functionalization, and the presence of active sites or hotspots that govern interactions with molecules, reactants, or pollutants. Self-assembly and supramolecular interactions further enable scalable fabrication of functional nanostructures in all three areas[78].

Surface chemistry plays a particularly critical role, as it determines colloidal stability in biological fluids, adsorption and activation of reactants in catalysis, and selective binding of contaminants in environmental systems(79). This convergence underscores nano-chemistry as a transferable design framework rather than an application-specific toolkit.

6.3 Divergent Design Requirements and Performance Metrics:

While sharing fundamental principles, each domain applies distinct performance metrics. Drug delivery systems are evaluated based on bioavailability, therapeutic index, pharmacokinetics, and safety profiles. Catalytic systems emphasize turnover frequency, selectivity, energy efficiency, and recyclability. Environmental nano-systems prioritize removal efficiency, operational cost, reusability, and environmental safety[80].

These divergent requirements necessitate domain-specific optimization strategies. For example, surface modifications that enhance cellular uptake may be unsuitable for catalytic reuse, while highly reactive catalysts may pose toxicity risks in environmental contexts. Recognizing these differences is essential for translating nano-chemical innovations across domains without compromising performance or safety[81].

7. Toxicity, Safety, and Regulatory Considerations:

The rapid expansion of nano-chemistry–enabled technologies has intensified concerns regarding the safety, toxicity, and regulation of nanomaterials. While nanoscale systems offer significant benefits in drug delivery, catalysis, and environmental remediation, their small size, high reactivity, and persistence raise unique biological, environmental, and ethical challenges that must be critically addressed to ensure responsible and sustainable application[82].

7.1 Nano-Toxicity Mechanisms

Nano-toxicity arises from physicochemical properties such as particle size, shape, surface charge, composition, and solubility. At the nanoscale, materials can readily interact with cellular membranes, proteins, and nucleic acids, leading to oxidative stress, inflammation, and genotoxic effects. The generation of reactive oxygen species is a dominant mechanism underlying nano-induced cytotoxicity, particularly for metal and metal-oxide nanoparticles.

Surface chemistry plays a decisive role in modulating nano-toxicity. Surface coatings, functional groups, and aggregation state influence cellular uptake and intracellular distribution, emphasizing the importance of nano-chemical design in mitigating adverse biological responses[83].

7.2 Environmental and Biological Accumulation:

Nanomaterials released into the environment may undergo transformation, aggregation, or interaction with natural organic matter, affecting their mobility and bioavailability. Persistent nanomaterials can accumulate in soil, water, and biological systems, leading to long-term ecological consequences. In biological systems, accumulation in organs such as the liver, spleen, and lungs has been reported for certain inorganic nanoparticles, raising concerns about chronic exposure and delayed toxicity[84]. Understanding the environmental fate and transport of nanomaterials requires integrated nano-chemical and ecotoxicological assessment, particularly for applications involving large-scale environmental deployment.

7.3 Regulatory Frameworks for Nanomaterials:

Regulatory oversight of nanomaterials remains a global challenge due to the diversity of nano-chemical systems and the lack of universally accepted testing protocols. Existing chemical regulations often inadequately address nanoscale-specific properties, necessitating adapted risk assessment frameworks. Regulatory agencies increasingly emphasize characterization, exposure assessment, and life-cycle analysis to ensure safe commercialization[85].

In the pharmaceutical sector, nano-enabled drug products are subject to stringent evaluation of quality, safety, and efficacy, whereas environmental and industrial nanomaterials face variable regulatory scrutiny depending on application and jurisdiction[86]. Harmonization of international guidelines remains a critical need.

7.4 Ethical and Sustainability Challenges:

Ethical considerations in nano-chemistry encompass transparency, risk communication, and equitable access to nanotechnology benefits. Sustainable nano-chemical design prioritizes green synthesis, biodegradable materials, and reduced environmental footprint. Balancing innovation with precaution is essential to maintain public trust and long-term societal acceptance of nanotechnology. The integration of ethical frameworks and sustainability principles into nano-chemical research and regulation is increasingly recognized as a prerequisite for responsible technological advancement[68].

8. Future Perspectives and Emerging Trends:

The future of nano-chemistry lies in its ability to integrate data-driven design, sustainability, and translational readiness while addressing domain-specific performance and safety requirements. Emerging trends indicate a shift from empirical development toward predictive, life-cycle–aware, and application-integrated nano-chemical systems.

8.1 AI-Assisted Nano-Material Design:

Artificial intelligence (AI) and machine learning are increasingly used to accelerate nano-material discovery by predicting structure–property relationships, optimizing synthesis parameters, and screening toxicity and performance in silico. AI-assisted design enables rapid identification of optimal particle size, morphology, and surface chemistry for targeted functions across drug delivery, catalysis, and remediation. These approaches reduce experimental cost and time while improving reproducibility and scalability[87,88].

8.2 Green and Biodegradable Nanomaterials:

Sustainable nano-chemistry emphasizes green synthesis routes using renewable resources, low-energy processes, and non-toxic reagents(89). Biodegradable nanomaterials derived from natural polymers, lipids, and bio-inspired inorganic systems are gaining prominence, particularly in biomedical and environmental applications. Such materials minimize long-term accumulation and ecological impact while maintaining functional performance[18].

8.3 Personalized Nanomedicine:

Advances in nano-chemistry are driving personalized nanomedicine, where carrier design is tailored to patient-specific physiology, disease state, and genetic profile. Nano-enabled platforms capable of responsive dosing, targeted delivery, and real-time monitoring are expected to improve therapeutic outcomes and reduce adverse effects. Integration with diagnostic data and AI tools will further enable precision design of nano-therapeutics[90].

8.4 Circular Economy and Sustainable Remediation:

Nano-chemical technologies are increasingly aligned with circular economy principles, emphasizing material recovery, reuse, and minimal waste generation. In environmental remediation, recyclable nano-adsorbents, regenerable catalysts, and magnetic separation strategies support sustainable water and soil treatment. Designing nanomaterials for repeated use and safe end-of-life disposal is critical for large-scale deployment[91].

8.5 Translational Barriers and Commercialization Strategies:

Despite laboratory success, translation of nano-chemical innovations to commercial products faces challenges related to scale-up, standardization, cost, and regulatory acceptance. Robust characterization protocols, life-cycle assessment, and early engagement with regulatory frameworks are essential to bridge the gap between research and application. Industry–academia collaboration and pilot-scale validation will play a decisive role in commercialization[92].

CONCLUSION:

Nano-chemistry has emerged as a transformative discipline that redefines the design, understanding, and application of chemical systems across multiple sectors by exploiting size-dependent physicochemical properties, surface chemistry, and quantum-scale phenomena. Through precise control at the nanoscale, nano-chemistry has enabled highly efficient and tunable systems that address long-standing challenges in drug delivery, catalysis, and environmental remediation. A central insight of this review is the strong cross-disciplinary synergy intrinsic to nano-chemistry, where common principles such as surface functionalization, self-assembly, and structure–property relationships unify diverse applications, allowing innovations in one domain to be translated effectively to others. This convergence fosters integrative and sustainable solutions while accommodating domain-specific performance and regulatory requirements. From a long-term perspective, nano-chemistry holds significant societal and industrial promise by supporting safer and more effective therapeutics, cleaner and more energy-efficient manufacturing, and advanced strategies for pollution control and resource recovery. As nano-chemical technologies continue to evolve toward real-world implementation, their responsible development, guided by safety, sustainability, and regulatory alignment, will be essential. Overall, nano-chemistry stands as a cornerstone of future scientific and technological progress, with enduring impact on healthcare, industry, and environmental stewardship.

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CONFLICT OF INTEREST:

The authors declare that they have no conflict of interest.

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