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REVIEW ARTICLE

Nanostructured materials: Synthetic strategies and their expanding roles in catalysis, drug delivery, and environmental remediation

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Abstract

Nanostructured materials comprising both discrete nano-objects with at least one external dimension below approximately 100 nm and nanostructured bulk or hierarchical materials that are assembled from nanoscale structural units even though the object itself can be macroscopic have grown from laboratory curiosities to becoming a key platform in the development of applications for controlling pollution, precision medicine, and catalysis. Through manipulation of size, shape, composition and surface chemistry, they can be precisely engineered to exhibit desired reactivity, optical properties, transport behaviour, and surface functionality arising from their high surface-to-volume ratio and unique quantum and interfacial effects. This review discusses the critical role of the different synthesis strategies, like top-down physical processes, bottom-up wet-chemical processes, template-directed processes, self-assembly processes, green and biogenic processes, and metal-organic framework (MOF)-based processes, on particle size, shape, crystallinity, and surface features. Progress in heterogeneous catalysis and single-atom catalysis is reviewed, considering increased accessibility of the active sites and better selectivity. Applications to nanomedicine and drug delivery are developed, including stimuli-responsive and targeted nanocarriers in the form of polymeric, lipidic, magnetic or MOF materials. The review also covers nanomaterial applications for environmental remediation in the field of heavy metal, dye, and emerging contaminant adsorption and sequestration applications. Finally, toxicity, classification of environmental fate, scalability, repeatability, and the impact of nanomanufacturing are examined. The next steps will require a combination of proven synthetic methods and application-specific design and sustainable manufacturing strategies.

KEYWORDS

Nanostructured materials; Nanocatalysis; Drug delivery; Nanomedicine; Environmental remediation; Nanotoxicology

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Introduction

The prefix "nano" represents the one-billionth of a meter, but the real interest in the nanoscale is not the number but the changes in the properties of matter when they are scaled down. As particle size falls below roughly 100 nm, the fraction of atoms located at surfaces and interfaces rises sharply; for a spherical particle this fraction scales approximately with the inverse of the radius, so it can increase by one to two orders of magnitude between the micron and few-nanometer scale, with the precise factor depending on material and morphology [1-4]. This rise in surface-atom fraction increases the specific surface free energy relative to the bulk cohesive energy, and, in the additional regime of quantum confinement (particle dimensions comparable to or smaller than the exciton Bohr radius or Fermi wavelength), discrete electronic and vibrational states emerge, and the band structure of semiconductors and metals becomes explicitly size-dependent [5,6]. These changes are not coincidental but the mechanism for virtually all of the applications covered in this review. A few nanometers across, a gold particle is catalytic for CO oxidation at temperatures at which bulk gold is inactive; a CdSe nanocrystal glows in colour determined by size, not by chemical composition, and a single-atom particle of Fe_2O_3 can be magnetically directed down the bloodstream [7-9]. By this reasoning, nanostructured materials are not a family, but rather a design space a set of rules that can be followed independently of each other so that size, shape, composition, crystallinity, and surface chemistry of nanostructured materials can be tuned for a desired physical or chemical response.

An area of great interest has emerged from this design space, moving from some pioneering discoveries to a more mature, interdisciplinary design space. Separation of single-layer graphene by Novoselov and Geim, development of reproducible hot-injection methods to make monodisperse CdE nanocrystals by Murray et al., and the discovery of ordered mesoporous silica (MCM-41) by Kresge et al. have been considered to provide the synthetic control necessary for making the application developments that have followed [8,10-12]. Meanwhile, the coordination chemists were developing an extremely porous MOF, and the colloid chemists used an already well-established citrate reduction method to produce gold nanoparticles in a domain of shape-controlled synthesis of metal nanoparticles [9,13,14]. Nanostructured materials underpin three application domains, which were historically developed by separate communities, but all share the need for a limited number of synthetic levers; the first is catalysis and adsorption where the ability to maximize the density and accessibility of active sites on catalytically active materials plays a key role in the application; the second is drug delivery where activity is tied to encapsulating, protecting and selectively releasing therapeutic payloads using nano structuring; the third is environmental remediation where, again, the ability to maximize the density and accessibility of active sites on pollutant-scavenging materials plays a key role in the application [15-25].

The organization of this review has been done to attempt to make the relationships among these three disciplines explicit, not as separate literatures. The classification and structure property relationships are repeated throughout all the nanostructured materials and are introduced in Classification and fundamental structure and property relationships. Because similar hydrothermal or sol–gel methods are commonly employed to prepare a water treatment adsorbent, an adsorbent for a drug, or a catalyst support, Synthetic strategies for nanostructured materials presents a systematic description of synthetic protocols, classified according to the mechanism of the synthesis, rather than by target application. The mechanisms, synthetic strategies, and the performance measurements that are relevant to the application are then chosen for catalysis, drug delivery, and environmental remediation, respectively. Questions of toxicology and environmental safety are likely to be encountered by

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any nanomaterial product intended for commercial use on a large scale in applications to catalysis, biomedical or environmental systems and are discussed in Nanotoxicology, environmental fate, and regulatory considerations. conclusion and future directions: translation challenges cover the translational challenges and future directions, while concludes (Figure 1) [26-29].

Novelty statement

This differs from the single-domain survey as it makes an explicit structure-synthesis-function bridge based on the same few fundamental synthetic levers: precursor chemistry, nucleation/growth control, templating, and post-synthetic surface engineering, which are re-parameterized through three separate, but interconnected application communities (catalysis, nanomedicine, environmental engineering). The review presents the synthesis routes side by side with the relevant performance metrics for each of the three reviewed application areas (catalysis, drug delivery and remediation) and shows explicit transferable design rules, which are typically not articulated in the domain-specific literature; the review is concluded by an integrated toxicological and regulatory outlook that is rarely presented along with synthesis-and-application reviews.

This positioning is distinct from recent broad nanomaterials reviews published in 2022-2026. General synthesis-and-properties surveys such as those of Rahman et al. and Silva et al. catalogue synthetic methods but do not carry a common set of performance metrics across catalysis, medicine and remediation; sustainability-oriented reviews such as that of Ren et al. and green-synthesis-focused surveys emphasize a single application sector, chiefly environmental or biomedical, rather than a cross-domain comparison; and holistic sustainability reviews such as that on harnessing nanostructured materials for sustainable development explicitly distinguish themselves from prior single-sector reviews but do not organize their comparison around the specific synthesis-structure-performance parameters used here [4,30-33]. The present review adds to this literature (i) a shared four-parameter design-rule framework (Classification and fundamental structure and property relationships) applied consistently across all three application sectors, (ii) synthesis-family comparisons that explicitly include reproducibility, scalability, energy demand and life-cycle criteria rather than yield or size alone, and (iii) an integrated, sector-differentiated regulatory and nano safety discussion.

Classification and Fundamental Structure and Property Relationships

Before classifying materials by dimensionality, it is useful to separate two related but distinct usages of the term "nanostructured material" used throughout this review. Nano-objects (nanomaterials in the strict sense) are discrete entities - nanoparticles, nanowires, nanosheets - for which essentially every external dimension is nanoscale (below approximately 100 nm), and whose properties are dominated by finite-size and quantum-confinement effects. Nanostructured bulk or hierarchical materials - mesoporous monoliths, aerogels, nanocomposites, and framework materials such as MOFs - are instead built from nanoscale structural units (pores, walls, or building blocks below 100 nm), but the object itself can be macroscopic and is handled, in a reactor or drug formulation, as a bulk solid; its performance derives from the internal nanoscale architecture (surface area, pore confinement, active-site density) rather than from whole-particle quantum confinement. Both usages recur below; where the distinction matters for a specific property, such as quantum confinement, which applies only to nano-objects, it is stated explicitly.

The traditional categorization of nanostructured materials is based on their dimensions. Quasi-zero-dimensional (0D) nanostructures possess nanocrystals with zero dimensionality in all three dimensions, and are generally observed to exhibit the most severe quantum confinement effects; their optical absorption and emission are size-tunable phenomena, first systematized by Alivisatos and subsequently expanded into device-relevant colloidal quantum dot technology [6,7,34-36]. The 1D nanostructures (nanowires, nanorods, and nanotubes) can be confined in two dimensions, albeit extended in the third dimension, resulting in anisotropic electrical transport properties through them, which are used in photocatalytic electrode architectures and in sensing applications. Two-dimensional (2D) nanostructures are structures that have been limited to just one dimension and typified by graphene and similar layered materials, and are described as possessing an extremely high in-plane surface area, as well as mechanical and electronic properties attractive as catalytic or adsorptive functionalization support. Three-dimensional (3D) nanostructured materials are created from nano blocks, whether in the form of mesoporous solids, nanocomposites, aerogels, or framework materials like MOFs, and yet can exhibit a macro-scale form, which can often be monolithic and can be easily manipulated in reactors, drug formulations, or filtration cartridges [4,12,13,37,38].

In each of the four dimensionalities, four parameters are the major ones that act as primary levers to control function. For semiconductors and some metals, size determines electronic energy levels via confinement and surface-to-volume ratio. The catalytic selectivity is crucial and dependent on the crystal structure when a reaction is taking place, because different crystallographic facets react with different types of reactants and intermediates, making them bind either strongly or weakly. Catalytic selectivity is decided by shape and faceting, where different crystallographic facets react with different types of reactants and intermediates, binding them either strongly or weakly [9,15]. In catalysis, the active-site motifs available for a reaction are determined by the intrinsic electronic structure of the composition, which can be a single element, an alloy, a core–shell heterostructure, or a multi-metallic high-entropy phase, as well as by its number, nature, and dimensionality [39]. Surface chemistry is key to controlling the stability, biocompatibility, and selective molecular recognition of the material in a colloidal state, and is the single most important parameter to ensure translation of a nanomaterial from the reaction flask to a working catalyst, drug carrier, or adsorbent [40,41]. The single dominant conclusion of this review is that, in essence, the vast majority of the synthetic approaches mentioned in synthetic strategies for nanostructured materials are methods for the control of one or more of these four parameters, and for any of the performance criteria mentioned in Nanostructured materials in catalysis through nanostructured materials in environmental remediation, the ability to control those parameters will have been key in a very large number.

Synthetic Strategies for Nanostructured Materials

As described below, in all the applications discussed later in this review, a synthetic decision is made first, but often one can think of this in terms of the mechanism by which the particles or pores are produced, rather than by the element or application, since a given mechanism (e.g., hydrothermal crystallization) can be used to make materials of different sorts, such as a catalyst support, drug nanocarrier, and water-treatment adsorbent [1,4,30]. In general, the synthetic methods are classified into six mechanistic classes: top-down physical methods, bottom-up wet-chemical methods, vapor-phase (chemical vapor deposition (CVD)) methods, template-directed and self-assembly methods, green/biogenic methods, and framework assembly (MOF/coordination-polymer) methods. These families are summarized in Table 1, along with their usual size control, benefits, and disadvantages.

The size ranges, advantages and limitations summarized in Tables 1-5 are representative values drawn from the synthesis and application literature discussed in the corresponding sections and the references cited therein; they are material- and method-dependent and should not be read as universal constants [1,4,7-9,12,14-16,20,23,28,37,42-46]. The same caveat applies to Table 4, whose loading strategies and translational limitations are drawn from the product labelling and clinical literature for each named nanomedicine (a case-study basis, not a universal value for the carrier class), and to the new quantitative synthesis comparison in Table 2, whose reproducibility, energy, waste and life-cycle figures are illustrative values reported for specific material systems (e.g., Ag_2S, ZIF-67, mechanochemical CO_2 catalysts) rather than universal properties of an entire synthesis family. Chemical notation, units and terminology (MOF, nanometer, TiO_2, CO_2, batch-to-batch) have been standardized throughout the revised manuscript.

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Top-down approaches

Top-down synthesis starts with bulk materials and involves mechanical, thermal, or energetic reduction to the nanoscale. The most common top-down process is high-energy ball milling, in which increasingly fine grain sizes can be obtained as the powder particles are broken repeatedly by the impact with one another of suitable milling media, and which avoids the use of solvents, is cheap and scalable and is thus extremely versatile for bulk production of nanocrystalline metal or alloy powders or for particle size reduction of oxide powders [4]. No chemical precursor or stabilizer is strictly necessary, so laser ablation always results in extremely clean particle surfaces of gold; these surfaces, which would otherwise require removal when using a chemical precipitate or stabilizer, are desirable in the areas of catalysis and biomedical use of the particles. Thin films of nanostructured metal oxides are widely deposited on a substrate using sputtering or other physical vapor deposition (PVD) processes that eject atoms able to condense as a thin film into large (therefore less structured) surface grains, and create heterojunctions (e.g. TiO_2/ZnO) with controlled stoichiometric ratios [47]. Wherever a predetermined array of nanostructures is needed in a precise register, and the desired pattern is arbitrary, these lithographic and etching processes, borrowed from the semiconductor industry, are essential, although often more time-consuming and expensive than the wet-chemical processes discussed below. All top-down approaches place some external form of size reduction on a preexisting bulk phase of interest and offer exceptional control over the composition, since no new chemical bonds will be formed (relatively fine control over the final particle-size distribution and shape uniformity is available, however, for bottom-up nucleation-and-growth chemistry) [4].

Bottom-up wet-chemical and vapor-phase approaches

Bottom-up synthesis achieves atom-by-atom or molecule-by-molecule growth of the nanostructures from dissolved precursors into atomic clusters and then to order by nucleation and growth, providing a much greater degree of control over size, shape, and monodispersed that does not occur with top-down comminution. Co-precipitation allows the simultaneous reduction or hydrolysis of metal salt in solution to obtain a nanocrystalline solid, and is the most common method used to produce magnetic nanoparticles of iron oxide and many oxide-based nano adsorbents, as it is simple, aqueous-based and easily scalable [1]. Beginning with Stober et al.'s pioneering work on monodisperse silica spheres by hydrolysis and polycondensation of molecular precursors, typically metal alkoxides, the method has come to be particularly favored for the exceptional control over the pore structure that it affords and has been extended, using structure-directing surfactants, to the templated mesoporous silica (MPS) discussed in Template-directed and self-assembly approaches [12,37,42, 48]. The technique of hydrothermal and solvothermal synthesis crystallization works on the premise that at high temperature and in an autogenous pressure environment, water or an organic solvent suffices to drive the metathesis of materials, allowing the formation of crystals as required, and is the workhorse for MOF crystallization and for nanocrystalline metal-oxide photocatalysts as well as for many of the layered double hydroxide or zeolitic adsorbents used in heavy-metal remediation [44,49]. This section also includes CVD, grouped here with the wet-chemical bottom-up routes for narrative convenience because, like them, it builds nanostructures atom-by-atom from a precursor; mechanistically, however, CVD is a gas-phase/vapor-phase deposition process rather than a solution-based wet-chemical method, and it is treated as mechanistically distinct in Table 1. CVD decomposes a vapor of a volatile precursor on a hot substrate to achieve excellent crystallinity of nanowires, nanotubes or nanostructured films, and it is the primary technique for the large-area growth of high-quality carbon nanotubes and carbon nanographene. The hot-injection method of Murray, Norris and Bawendi took a precursor solution of a semiconductor to the nucleation region and injected it rapidly into the hot coordinating solvent to immediately trigger a brief nucleation burst, followed by diffusion-limited growth, and continues to be the standard method for generating narrow-sized emission lines and monodisperse semiconductor nanocrystals [8]. Last, the citrate-reduction procedure discovered independently by Turkevich showed that the size of gold nanoparticles could be controlled from approximately 10 to 100 nm by simply adjusting the citrate/reducing/stabilizing agent and/or metal salt ratio; subsequently, this concept was generalized to shape-directing surfactants and halide additives, and is now the basis of shape-controlled synthesis of anisotropic gold and silver nanocrystals for applications in plasmonics and nano catalysis [9,14,35,50].

Template-directed and self-assembly approaches

Template-directed synthesis is a precipitation reaction that is driven in an ordered fashion by a sacrificial or structure-directing scaffold. In the soft template method, an inorganic precursor is condensed around self-assembled surfactant micelles (as in the original MCM-41 synthesis), which are then removed by calcination or extraction, yielding a periodic mesoporous framework the pore diameter of which can be controlled by the lengths of the surfactant chains and/or the introduction of pore swelling agents [4,12,37]. Hard templating: the rigid template (e.g., anodized aluminium oxide, colloidal silica, or mesoporous carbon) is first infiltrated with a precursor which is transformed in the template to the desired nanostructure, and then the template is dissolved to create an inverse replica, as this method is especially useful for achieving inverse structures such as hollow, yolk-shell, and hierarchically porous structures, which are difficult to achieve by direct precipitation. The self-assembly process, in its general sense, also leads to the spontaneous and organized arrangement of pre-prepared nanocrystals that are assembled by van der Waals, dipolar, or entropic forces, the effects of which can not only provide new optical and electronic properties, but can also make the redispersion of nanocrystals in solution more difficult if the colloidal stability is not sufficiently maintained [51].

Green and biogenic synthesis

Considering the hazards and costs of numerous chemical reducing agents (sodium borohydride or hydrazine) and organic solvents commonly used in traditional wet-chemical synthesis, green synthesis makes use of plant extracts, microbes, or biomolecules as both reducing and capping agents. Plant-mediated synthesis utilizes the wide range of phytochemicals present in the leaves, roots, and fruit extracts, such as flavonoids, phenolics, terpenoids, and proteins, that bring the metal ions to the zero-valent or oxide nanoparticle state and also adhere to the nanoparticle surface to stop further shape evolution [40,52,53]. The generalized mechanism involves the interaction of the functional groups of the phytochemicals with the metal ions, electron transfer and reduction, nucleation process, and finally, capping-mediated stabilization against aggregation [40]. In similar fashion to conventional wet chemistry that uses nucleation and growth control parameters as the main tuning levers to control particle size and morphology, the following parameters can likewise be used as the principal tuning levers in green synthesis: the temperature of the reaction, the concentration of the extract, pH and the ratio of precursors to extract; and, in many reported cases, the size and shape of the particles in green synthesis are comparable to chemically synthesized particles, with similar or greater antimicrobial, catalytic and photocatalytic activity compared to chemically prepared particles [41,54,55]. The microbial and fungal synthesis adds to this argument that reductases of bacteria, fungi, and algae can also provide an additional pathway toward biogenic nanoparticles, at a much larger scale, which may be more reproducible.

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Table 1. Comparative overview of principal synthetic strategies for nanostructured materials.

Strategy	Representative techniques	Typical size / Morphology control	Key advantages	Key limitations
Top-down (physical)	Ball milling, laser ablation, sputtering/PVD, lithography	10-200 nm; broader size distribution	Scalable, solvent-free, high purity (laser ablation)	Coarser size control, high energy input, possible contamination from milling media
Bottom-up (wet chemical)	Co-precipitation, sol-gel, hydrothermal/solvothermal, hot-injection	1-50 nm; narrow, tunable distributions	Fine size/shape control, high monodispersity, tunable composition	Solvent/precursor cost and toxicity, batch-to-batch variability at scale
Vapor-phase (CVD)	Chemical vapour deposition (nanowires, nanotubes, nanostructured films)	Film thickness / nanowire-nanotube diameter set by precursor flux, substrate temperature and deposition time; high crystallinity	Excellent crystallinity, large-area growth, direct substrate/device integration	High processing temperatures, vacuum/gas-handling infrastructure, substrate-compatibility constraints
Template-directed / self-assembly	Soft templating (surfactant/block copolymer), hard templating, colloidal self-assembly	2-50 nm pores; ordered mesostructured	Precise, tunable porosity; hierarchical/hollow architectures	Template removal step adds cost and complexity; possible structure collapse
Green/biogenic	Plant extract-, microbial-, and fungal-mediated reduction	5-80 nm; extract-dependent	Low toxicity, low cost, ambient conditions, inherent capping biomolecules	Batch reproducibility and yield depend on biological variability
MOF / coordination assembly	Solvothermal, microwave-assisted, mechanochemical	Sub-micron crystals; tunable pore aperture	Exceptional porosity and tunability; post-synthetic modification	Hydrolytic/chemical stability limits; scale-up and solvent recovery challenges

Table 2. Representative quantitative comparison of synthesis-family reproducibility, scalability, energy use, waste generation, and sustainability/life-cycle indicators (values are illustrative, system- and process-dependent, and drawn from the cited case studies rather than universal for the family).

Strategy	Reproducibility (Representative)	Scalability (Representative)	Energy input (Representative)	Solvent/precursor demand & waste (Representative)	Sustainability / LCA note
Top-down (physical)	High compositional reproducibility (no wet chemistry); particle-size distribution typically broader and less batch-consistent than solution routes	Routine at kg-to-tone scale (industrial milling, sputtering)	High, continuous mechanical/thermal input (e.g., ball milling, PVD)	Minimal solvent use; milling-media wear/contamination is the main waste stream	Avoids solvent-related life-cycle burden but energy intensity dominates footprint [1,4]
Bottom-up (wet chemical)	Good at lab scale under controlled nucleation; batch-to-batch variability rises sharply on scale-up	Demonstrated pilot-to-industrial for some routes (e.g., aqueous co-precipitation); harder to preserve nucleation-burst control above small-batch volumes	Strongly route-dependent: hydrothermal synthesis of Ag2S nanoparticles has been reported at ~10.9 kg CO_2-eq per kg product versus ~543 kg CO_2-eq per kg for flame-spray-pyrolysis routes to a comparable product (>50-fold higher) [43]	Organic solvents, surfactants and metal-salt precursors are the dominant waste stream; solvent recovery is rarely closed-loop at lab scale.	Aqueous co-precipitation routes are comparatively favorable; solvothermal routes using DMF or similar solvents remain a recognized life-cycle hotspot [43,48]
Vapor-phase (CVD)	High film/nanostructure uniformity for a fixed reactor geometry; reactor-to-reactor transfer is non-trivial	Proven for large-area film and graphene growth; limited by vacuum/gas-handling capital cost rather than chemistry	High; sustained high-temperature and/or vacuum operation is energy-intensive relative to solution routes.	Precursor and carrier-gas consumption; halogenated by-products in some CVD chemistries	Energy footprint is the dominant life-cycle driver; dedicated life-cycle assessments of lab-scale CVD nanomaterial routes remain scarce.

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Table 2 (continued)

Strategy	Reproducibility (Representative)	Scalability (Representative)	Energy input (Representative)	Solvent/precursor demand & waste (Representative)	Sustainability / LCA note
Template-directed / self-assembly	Pore ordering is reproducible under fixed surfactant/precursor ratios; the template-removal step adds a further variability source.	Surfactant cost and the template-removal step (calcination/extraction) limit throughput	Calcination adds a distinct high-temperature energy cost on top of the initial condensation step.	Extracted or calcined template material becomes an additional waste stream unless recovered.	Recyclable hard templates (e.g., silica, carbon) improve the life-cycle profile relative to single-use soft templates.
Green/biogenic	Batch-to-batch variability tied to extract or biomass composition (species, season, extraction batch) is a well-documented limitation.	Demonstrated at gram-to-multigram lab scale; sourcing consistent, large-volume biomass extract is the main scale-up bottleneck.	Comparatively low; ambient-temperature, aqueous-based conditions are the norm.	Biomass/extract residue is typically low-hazard and is itself often a waste-valorization stream (agricultural/forestry by-products)	Consistently reported as the lowest solvent/energy footprint of the families compared here, though rigorous life-cycle data remain sparser than for conventional routes [43]
MOF / coordination assembly	Crystallinity/phase purity reproducible under a fixed solvothermal protocol; heat- and mass-transfer deviations appear on scale-up	Mechanochemical and microwave-assisted routes are explicitly pursued to enable scale-up, cutting crystallization time from days to minutes [49,56]	Mechanochemical (ball-milling) synthesis has been reported to cut energy use by roughly 20-50% and waste by 60-90% relative to conventional solvothermal routes in a recent review of CO_2-catalyst-oriented Mechan synthesis [48]	Solvent use (e.g., DMF, methanol) is a recognized life-cycle hotspot, accounting for up to ~90% of total impact in some solvothermal MOF studies; metal-precursor production (e.g., cobalt nitrate for ZIF-67) can dominate toxicity-related impact categories [59]	Solvent-free/mechanochemical and aqueous routes are the clearest lever for improving MOF life-cycle performance without sacrificing porosity [48,59]

Table 3. Representative classes of nanostructured catalysts, their synthetic origin, and catalytic role.

Catalyst class	Typical synthesis route	Structural feature exploited	Representative catalytic role
Shape-controlled metal nanocrystals	Seed-mediated wet-chemical growth with facet-directing surfactants	Facet-specific atomic arrangement	Selective hydrogenation, oxidation, electrocatalysis
Single-atom catalysts	Wet impregnation / atomic layer deposition on oxide or carbon supports	Isolated, coordinately unsaturated metal centers	CO oxidation, selective hydrogenation with near-unity atom utilization
Magnetic-nanoparticle-supported catalysts	Co-precipitation core + silica/polymer shell + catalyst grafting	Superparamagnetic recoverable core	Homogeneous-catalyst-like selectivity with magnetic recovery
High-entropy alloy nano catalysts	Arc melting/dealloying (top-down) or co-reduction (bottom-up)	Multi-element solid solution, lattice distortion	Electrocatalytic H2/O2/CO_2/N2 redox reactions
MOF-based catalysts	Solvothermal / microwave assembly; post-synthetic metalation	Uniform pore/channel confinement, tunable acid sites	Shape-selective cycloaddition, condensation, nanoreactor catalysis
Carbon-supported catalysts	CVD-grown CNT/graphene + covalent or non-covalent immobilization	High surface area, tunable surface functional groups	Heterogeneous asymmetric organocatalytic

Table 4. Principal Nanostructured drug carrier platforms, loading mechanism, and release trigger.

Carrier platform	Typical synthesis route	Drug loading mechanism	Representative release trigger
Solid lipid / nanostructured lipid carriers	High-shear homogenization, microfluidic mixing	Hydrophobic drug entrapment in lipid matrix	Matrix erosion / body-temperature melting
Polymeric (PLGA, chitosan) nanoparticles	Nanoprecipitation, emulsification-solvent evaporation	Physical entrapment or covalent conjugation	Polymer hydrolysis; colon-specific pH shift
Mesoporous silica nanoparticles	Soft-templated sol-gel condensation (surfactant micelle)	Pore-channel adsorption / co-condensation	pH-, redox-, or enzyme-cleavable pore-capping gatekeepers

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Table 4 (continued)

Carrier platform	Typical synthesis route	Drug loading mechanism	Representative release trigger
Nanoscale MOFs	Solvothermal, microwave-assisted, mechanochemical	High-capacity pore/channel encapsulation	pH, redox, or thermal framework/linker responsiveness
Magnetic iron-oxide nanocarriers	Aqueous co-precipitation + polymer/silica coating	Surface conjugation or shell encapsulation	External magnetic field-guided accumulation
Quantum-dot theranostic probes	Hot-injection colloidal synthesis	Surface conjugation to drug/targeting ligand	Receptor-mediated endocytosis; imaging-guided delivery

Table 5. Representative clinically approved or clinically advanced nanomedicines, carrier class, application, loading strategy, and major translational limitation.

Nanomedicine (Carrier class)	Carrier / Material	Approved therapeutic application	Loading strategy	Major translational limitation
Doxil® / Caelyx® (liposomal)	PEGylated liposome	Doxorubicin; ovarian cancer, Kaposi's sarcoma, myeloma	Remote (ion-gradient) loading of drug into pre-formed liposome	Hand-foot syndrome; no interchangeable generic despite expired patents
Abraxane® (protein-bound)	Albumin nanoparticle	Paclitaxel; metastatic breast, lung and pancreatic cancer	Non-covalent binding of drug to albumin during high-pressure homogenization	Batch-to-batch albumin variability; cost of GMP protein processing
Onpattro® (lipid nanoparticle)	Ionizable lipid nanoparticle	Patisiran siRNA; hereditary transthyretin amyloidosis	Electrostatic/ionizable-lipid encapsulation of siRNA	Cold-chain requirements; immune/infusion reactions; liver-biased biodistribution
Vyxeos® (liposomal)	Non-PEGylated liposome (fixed drug ratio)	Daunorubicin + cytarabine; high-risk acute myeloid leukaemia	Co-encapsulation preserving a fixed synergistic drug ratio	Complex manufacturing to maintain ratio; narrow indication
Feraheme® (ferumoxytol)	Dextran-coated iron-oxide nanoparticle	Iron-deficiency anaemia; off-label MRI contrast	Aqueous co-precipitation of iron oxide, dextran coating	Rare but serious hypersensitivity reactions; interference with subsequent MRI
Kadcyla® (antibody-drug conjugate)	Antibody-drug conjugate (not a classical nanocarrier)	Trastuzumab emtansine; HER2-positive breast cancer	Covalent linker conjugation of cytotoxic payload to antibody	Linker/payload stability in circulation; cardiotoxicity monitoring needed

Metal-organic framework (Coordination assembly) synthesis

MOFs are self-contained and stand within a category of novel synthetic frameworks in which the structure is built by the following design principles introduced by Yaghi et al.: Based on discrete metal ions or metal-cluster secondary building units, the structure is built from a reticular assembly of the metal ions or metal clusters with polytopic organic linkers to create a permanently porous, crystalline coordination network [13]. This thermodynamic control is best achieved by hours to days of heating together of metal salt and linker inside a sealed container in a polar aprotic solvent (often dimethylformamide), which is the most widely used preparation route for MOFs [49]. More recently, some microwave-assisted [49] and mechanochemical (ball-milling without solvents) crystal syntheses have been developed which both reduce crystallization times from days to minutes, and also reduce solvent waste, for the biomedical and environmental applications discussed below where both these factors are important [56]. Post-synthetic modification, i.e., deliberate functionalization of a pre-made MOF's linkage, metal units or the internal pore surface, has emerged as the dominant means of incorporating functionality into an otherwise generic topology and is the focus of the discussions in Nanostructured Materials in Catalysis, Nanostructured Materials in Drug Delivery and Nanostructured Materials in Environmental Remediation [57,58].

Synthesis-performance linkages: A unifying principle

The overall theme of this section is that there is no synthesis work preceding the real application work, but rather that every parameter synthesized is directly related to a certain measurement of performance. Nucleation burst duration during the synthesis via hot-injection or co-precipitation is important in determining the particle size distribution, catalytic surface area, drug payload-to-carrier mass ratio, and external surface area for pollutant adsorption. The pore diameter, which is set by the surfactant or template choice, dictates access to internal binding sites of the mesopores and whether any drug molecule or pollutant will be able to access them or not. The variety of surface catalytically active ensembles is determined by the precursor stoichiometry in the synthesis of alloys and high entropy nano catalysts [39]. Being aware of these direct connections is the organizing principle throughout the rest of this review; synthesis and applications are not viewed as different literatures.

Nanostructured Materials in Catalysis

Many industrially relevant heterogeneous reactions take place at the catalyst surface only, and thus decreasing the diameter of a catalyst particle from micron to nanometer scale increases the mass-specific activity of a particular amount of a (often precious) catalyst metal [15,16]. In addition to this surface area argument, there are three additional levers available for controlling catalytic performance that bulk materials lack:

(1) Control over facet exposure of the cavity surface,

(2) Alloying/ensemble control, and

(3) Support-mediated electronic modulation.

Developing new and improved nanocrystal catalysts via facet and

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shape control.

Different crystallographic facets display different bonding strengths for reactants, intermediates, and products, and shape-controlled synthesis, defined as the modification of growth conditions to favour the expression of a given crystallographic facet, has emerged as a key approach to fine-tune the catalytic selectivity of nanocrystals [9,15]. The methodology pioneered for shape-controlled synthesis of the gold and silver nanocrystals has been expanded to the platinum group components to yield cubes, octahedra, and also more complex concave or branched nanocrystals, with crystals that feature exposed facets correlated to the desired reaction process, such as hydrogenation, oxidation, or electrocatalytic fuel-cell chemistry [9,14,15].

These structure-selectivity relationships are most usefully expressed through standard catalytic metrics: conversion (fraction of reactant consumed), selectivity toward the desired product, turnover frequency (TOF, catalytic events per active site per unit time) or turnover number (TON, total events per site over catalyst lifetime), and stability under repeated cycling or continuous operation. For shape-controlled metal nanocrystals, exposing a higher density of low-coordination edge and corner atoms, or a specific low-index facet, has been reported to raise TOF by roughly one to two orders of magnitude relative to a poorly faceted particle of the same composition in several specific structure-sensitive systems - notably Pt- and Pd-group facet-controlled nanocrystals for CO oxidation and selective hydrogenation - and this magnitude should not be assumed to generalize to structure-sensitive catalytic reactions or facet combinations beyond those reported; while changing facet or particle size can shift product selectivity between competing reaction pathways, the size, morphology, exposed facets, composition and metal-support interaction should therefore be reported alongside, not instead of, these performance metrics for each specific reaction studied [9,15].

Single-atom and sub-nanometer catalysts

Taking nano structuring to its extreme, single-atom catalysis is based on binding individual metal atoms on a support so that, in principle, every metal atom is catalytically accessible and not the metal atoms in the interior, which remain inactive. Single-atom sites do result in a more structurally well-defined structure, and they also possess the opportunity to catalyze selectivity with a precision on par with homogeneous, molecular catalysts while maintaining the practicality of recovering and reusing the catalyst as a heterogeneous solid; the years since this concept was articulated as "arguably the most active new frontier in heterogeneous catalysis" have seen a fast pace of development in this field [16]. As an alternative design, catalysts can be homogeneous with the proteins or catalytic complexes that carry the catalytic function inside the magnetic core, to obtain the selectivity of a homogeneous catalyst but with a heterogeneous catalyst which can be easily removed from the reaction mixture by separating it from a simple external magnet [10]. It is important to distinguish isolated single-atom sites, in which every metal atom is individually anchored to the support with no metal-metal bonding, from sub-nanometer clusters of a few to a few dozen atoms, which retain some metallic bonding character and correspondingly different electronic and catalytic behaviour; confirming true atomic dispersion (rather than an undetected mixture of single atoms and clusters) generally requires the combination of aberration-corrected scanning transmission electron microscopy, X-ray absorption spectroscopy (EXAFS/XANES), and CO-probe diffuse-reflectance infrared spectroscopy, since no single technique is conclusive on its own [16].

Multi-metallic and high entropy nano catalysts

Ensemble- and ligand-effects can drive a shift in binding energies for two or more metals in a single nanocrystal that is otherwise impossible using a single element; and recently, high entropy alloys (HEAs), which involve five or more different elements in a near equimolar ratio in a single nanostructured solid-solution, have been extended to include two or more metals in one structure [39]. High entropy nano catalysts provide four interrelated effects that create an enormous combinatorial design space for controlling activity, selectivity and stability in challenging hydrogen-, carbon, oxygen, and nitrogen-based redox reactions in catalysis, namely the high entropy effect (also known as configurational entropy, which stabilizes a single solid solution phase over ordered intermetallic), lattice distortion (which stretches and thus tunes surface bond lengths), sluggish diffusion (which leads to exceptional thermal and sintering stability), and the cocktail effect (which refers to the catalytic behaviour of the alloy not being the sum of its parts but rather its product).

Metal-organic framework and oxide supported catalysis

MOFs feature two unique catalytic strategies. First, the inherent Lewis and/or Brønsted acid sites of the framework structures can be utilized as catalytic active sites without requiring any additional or external groups. For example, defect-engineered frameworks, in short reaction times and under microwave illumination, have been utilized directly as dual-acidic heterogeneous catalysts for condensation and cycloaddition reactions needed to obtain the heterocyclic species with high yields [58]. Second is the framework's regular porosity, which can also be used as a nanoreactor or a scaffold on which metal (or metal-oxide) nanoparticles are grown and stabilized /combined with the intrinsic activity of the nano catalyst embedded in the framework, and hence a "ship-in-a-bottle" [57]. In addition to MOFs, oxide nanocrystal catalysis takes advantage of the ability to have precise control over the size, shape and exposed facets on the nanocrystal to control its activity and selectivity, from CO oxidation to selective partial oxidations, with the design principles for both material classes used to optimize activity and selectivity increasingly being incorporated into a common framework that incorporates common electronic and geometric design parameters for both [15]. Nitride nano catalysts, especially early transition-metal nitrides, have been found as a lower-cost alternative to noble-metal nano catalysts in ammonia decomposition and related biomass and energy transformations for a hydrogen-based energy economy separately [60].

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Carbon-supported and green nano catalysis

Carbon nanomaterials such as graphene, carbon nanotubes and fullerenes are used as supports for organ catalysts, metal nanoparticles and metal-organic complexes which are immobilized to utilize them for heterogeneous asymmetric catalysis, where the high surface area and chemical inertness of carbon materials along with their simple functionalization (covalent or non-covalent) makes it possible to reach the high enantioselectivity of homogeneous chiral catalysts, while keeping their recoverability and reusability [61]. Concurrently, a significant and continually growing amount of research has been reported involving the use of green-synthesized metal-oxide and bio-nanocomposite nano catalysts in the synthesis of

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multicomponent heterocycles, which are synthetically important for pharmaceutical synthesis using magnetically recoverable nano catalysts, finding that the yields of the reactions using the green nano catalysts are comparable or superior to those attained with conventional catalysts and that these catalysts can be recovered and reused in a variety of reaction cycles with ease, recovering the catalyst through magnetic separation method [17]. Nano catalysis moves beyond batch reactors by being placed as thin layers (nano catalyst layers) on channel walls through sol-gel, layer-by-layer polyelectrolyte, or (bio) inspired electroless deposition protocols, which enhances mass and heat transfer and facilitates the cleaning of a catalyst layer [62].

Nanostructured Materials in Drug Delivery

The classic small-molecule chemotherapies and bio-therapeutics are often not just sub-optimal with respect to lack of systemic efficacy, but also sub-optimal with respect to their pharmacokinetics: especially a rapid clearance rate, sub-optimal biodistribution, low aqueous solubility, and a narrow therapeutic window, relationship between efficacy and systemic toxicity [20,63]. Using nanostructured drug carriers, the design allows for the solubility of the drug to be optimized, protecting the drug from premature degradation, extending drug circulation time, and enabling passive targeting and accumulation in leaky blood vessel tumors and pinpointed receptor-mediated targeting [18,20,64]. This section introduces the main classes of drug carriers based on material chemistry, and examines how material synthetic control in the approach presented relates to corresponding aspects of drug loading capacity, drug release profile, and targeting.

Formulation optimization of nanocarriers

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) are based on either solid or semi-solid lipid carrier matrices, which are created by high shear homogenization or microfluidic mixing, and encapsulate hydrophobic drugs, providing better physical stability and more controlled release than previous liposome drug delivery systems [65]. Similarly, nano emulsions, which are thermodynamically metastable dispersions of oil and aqueous phases stabilized by surfactant, have also been widely explored for a variety of industrial and pharmaceutical applications because the dispersion of droplets can be adjusted to be sub-200 nm [66]. The polymeric nanoparticles, which are constructed from biodegradable polymers (such as poly(lactic-co-glycolic acid) (PLGA) or from natural biopolymers (such as chitosan), could exhibit pH-triggered or drug release rate tunability depending on polymer molecular weight, crystallinity and copolymer ratio, and chitosan-based oral NP formulations have been receiving interest in the treatment of colorectal cancer due to the mucoadhesive property of the polymer and its potential as a colon-specific delivery carrier where the drug release can be pH-triggered, protecting the payload in the upper gastrointestinal tract [67]. In addition to single-drug carriers, the co-delivery of two or more therapeutic molecules simultaneously within a single carrier – for instance, chemotherapeutic and immunotherapeutic molecules, or, more recently, chemotherapeutic and phytochemical or phytotherapeutic molecules – represents a method of achieving synergy against multidrug-resistant malignancies in particular, because only a single administration is necessary, with optimal therapeutic properties.

Mesoporous silica nanoparticles

Since their initial proposal as drug nanocarriers in 2001 mesoporous silica nanoparticles (MSNs) have been one of the more widely studied inorganic nanocarrier platforms due to their high specific surface area, large pores (which can be tailored through the preparation method), their ability to be easily surface functionalized, and their generally good biocompatibility [6,58]. One-step soaking or more intricate co-condensation approaches are used to produce, in an ordered mesopore channel, a wide variety of "gatekeeper" chemistries designed to allow simple drug molecules to enter while preventing any leakage until a specific physiological or intracellular environment is reached; these include pH-cleavable acetal linkages, redox-responsive disulfide bonds, enzyme-cleavable peptide caps, and supramolecular nano valves based on cyclodextrin or pillar arene macrocycles [7,9,32]. The most well-known pH gradient is between healthy tissue and the acidic tumor microenvironment or endosomal compartment, and pH-responsive MSN gatekeeper strategies have been sorted into four general structural classes based on the chemistry of the capping group [7]. This is taken one step further in enzyme-responsive MSN systems where two active targeting mechanisms, hyaluronic acid and monitoring of tumor cells, are functionalized onto one MSN platform, in addition to the enzyme lability, such that multiple targeting/hybrid systems enable a tunnel-to-tunnel drug delivery with compartmentalized release operations, using hyaluronidase- and protease triggered release of the drug from the hyaluronidase (HA) functionalized MSNs with capping of the platform by gelatin cross linked with hyaluronidase and protease (HYAL- and PROT-res respectively) [14].

Metal–organic framework nanocarriers

The striking surface area and the tunability of the pore size of MOFs have resulted in the development of an exclusive class of drug delivery carriers known as nanoMOFs that allow for high loading capacities for drug molecules, much higher than those afforded by mesoporous silica or polymeric carriers; and, in principle, the biodegradability of the framework can be modulated by carefully selecting the metal node to prevent concerns of long-term accumulation. [48,50]. The two most prevalent nanoMOF preparation methods are the hydrothermal and solvothermal synthesis methods; the microwave-assisted and mechanochemical variants of these are quicker ways to achieve crystallization for pharmaceutical-scale production [49]. Post-synthetic functionalization of the MOF structure by insertion of nanoparticles with noble-metal functionality, magnetic or carbon-based functionality, into the pore network results in nanohybrid MOF composites that possess imaging and/or photothermal or magnetic targeting functionality of the inserted nanoparticles, combined with a drug loading capacity of the MOF structure, and their potential applications have been explored in the fields of cancer therapy, antimicrobial treatment, wound healing, and neurodegenerative disease treatment [57]. Design principles employed in the construction of MSN gatekeepers are also applied to focus on the science of targeted drug delivery using a variety of nanoMOFs, which have already been reported to release drugs in response to changes in pH, redox potential, and temperature in the last decade [70].

Magnetic, quantum dot and theragnostic nanocarriers

Superparamagnetic iron-oxide nanoparticles (SPIONs), which are the most extensively synthesized preparatory route being in the aqueous phase and having the ability to carry drugs or genes, are also easily manipulated with an external magnetic field, and their magnetic properties act as a contrast agent in MRI, which makes these nanoparticles a promising platform for both therapeutic and diagnostic ("theragnostic") applications. The fluorescence of quantum dots (whether cadmium chalcogenide or, more often than not, heavy-metal-free carbon- and silicon-based) is size-tunable and photostable, which allows them to be used for the real-time tracking of the biodistribution and cellular uptake of nanocarriers, not only as a fluorescent 'label' but as an integrated part of multifunctional theragnostic nanoplatforms [42,71]. Active targeting involves the surface binding of an antibody, antibody fragment, peptide or small molecule ligand that binds to a receptor that is overexpressed on the target cell, and is deployed on top of passive, size-dependent tumor accumulation, to further localize the dose of nanomedicine at the intended target site; this two-step targeting approach has been reported for several clinically advanced nanomedicines and carrier types, though not all approved products use active targeting - Doxil and Abraxane, for example, rely primarily on passive accumulation (Table 4) [20,64]. The remainder of this section summaries which of these platforms have reached clinical use and the translational challenges that remain.

Several products based on nanoparticles are approved drugs, including liposomal (e.g., doxorubicin) and albumin-bound (nab-, e.g., paclitaxel) formulations of established chemotherapeutics;

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antibody-drug conjugates and antibody-targeted nanoparticle conjugates are an emerging pathway for actively targeted nanomedicines, including agents targeting the HER2 receptor in breast cancer [21]. Table 4 summaries representative clinically approved or clinically advanced nanomedicines across carrier classes, together with their major translational limitations. However, many of the tests included in the wider literature on the delivery of nanoparticles to biological targets allude to the same translation hurdles: poor and formulation-dependent drug-loading capacity, colloidal and chemical stability in biological fluids before administration and after delivery, inadequate understanding of how the protein corona that forms on the surface of a nanoparticle in biological fluids will affect the targeted functionality and inability to scale laboratory-scale synthesis to good manufacturing practice (GMP) production with batch-to-batch reproducibility [20,63]. These formulation-level barriers sit alongside a distinct, materials-intrinsic set of barriers to systemic translation: rapid opsonization and sequestration by the reticuloendothelial system/mononuclear phagocyte system (RES/MPS), predominantly in liver and spleen, which alters biodistribution away from the intended target tissue; the protein corona, which forms within minutes of blood contact and is itself a major determinant of RES/MPS uptake and subsequent cellular recognition rather than a separate consideration; and immunogenicity or complement-activation-related infusion reactions to carrier components (e.g., PEG, ionizable lipids), of the kind reported for several platforms in Table 4. It is worth stressing that only the liposomal, albumin-bound and lipid-nanoparticle carrier classes summarized in Table 4 have reached this level of clinical validation; the polymeric, mesoporous-silica, magnetic and quantum-dot platforms discussed remain preclinical or early-clinical, and their translational barriers, while overlapping with those above, have generally not yet been tested at GMP manufacturing scale. Nano-trials that address tumor-specific resistance mechanisms like the interaction between nanoparticles and programmed cell death pathways (pyroptosis, apoptosis, and necroptosis) are an active field of current research for optimization of the success rate of preclinically promising nanomedicines, down to clinical translation.

Nanostructured Materials in Environmental Remediation

Heavy metals, synthetic dyes, pharmaceuticals, and other emerging organic contaminants are still amongst the most critical environmental problems in the world [40], and conventional water treatment technologies such as coagulation, sedimentation, and biological treatment using activated sludge often fail to achieve the level of contaminant removal required by increasingly stringent regulations for trace pollutants [45,72]. Nanostructured materials can be used towards this end in two general ways, either by simply binding the contaminant onto the surface of the nanomaterial with high surface area, or by introducing reactive oxygen species produced by the nanomaterial (usually a semiconductor photocatalyst) that will mineralize the pollutant into less harmful products [45,25]. The nanoscale format is often found to be significantly better both in terms of amount of adsorbent/catalyst per unit of mass as well as the quantum efficiency of the photocatalytic reactions, compared to a conventional granular adsorbent/catalyst [23,44,73].

Heavy metal removal by nano adsorbents

Unlike organic pollutants, heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn) are elements and are therefore not biodegradable; they can only be transformed in oxidation state, immobilized, or physically removed from water, so their selective removal from industrial and mining effluents is an important application for nano adsorbents [45,74]. Depending on the nanomaterial and the metal species involved, this removal proceeds through several distinct mechanisms - surface adsorption and complexation, ion exchange, precipitation as an insoluble phase, chelation by surface-bound ligands, or, for redox-active metals such as Cr (VI), photocatalytic reduction to a less mobile or less toxic oxidation state - and these mechanisms are not interchangeable descriptions of the same process. Some nanomaterials such as metal-oxide nanomaterials, zeolites, chitosan-based nanocomposites, and ferrite /magnetic nanoparticles have been designed as nano adsorbents where the surface of the nanomaterials has been systematically functionalized for increased binding affinity and selectivity for specific metal ions [45,75]. The latter can offer adsorption capacity in excess of 1300 mg of copper (II) per gram and can be reused for several cycles of treatment, while one of the composite adsorbents (rice-husk-biochar-ZIF-67), comprising a high surface area, functional sable host and a metal oxide guest phase, was reported to deliver more than 70% adsorption efficiency (250–300 mg of copper (II) per gram) [44]. Magnetic nano adsorbents fall in an especially desirable category since, in the same way as nano catalysts can be recovered from the water by the magnetic field of a reactor, the spent nano adsorbent can be withdrawn from treated water without the need for the energy-intensive processes of filtration or centrifugation, thereby overcoming one of the major challenges to widespread deployment of nanomaterials for water processing: the cost [23,76]. Recoverability is, however, only the first half of the sustainability case: what happens to the recovered material once it is saturated or spent, determines whether magnetic recovery translates into a genuinely lower-impact process overall. In addition, nanocellulose, nanolignin and nanoxylan adsorbents are increasingly derived from various streams of agricultural and forestry waste and continue to show how the same green chemistry principles applied to nanoparticle synthesis continue to be extended, in this case, to the performance characteristics of the adsorbent material itself.

Use of photocatalytic degradation for the disposal of organic pollutants

With semiconductor photocatalysts, like TiO_2 and ZnO, UV (and, in band-gap-engineered heterojunction materials, visible) light produces electron-hole pairs; the holes oxidize the water or hydroxide molecule, forming hydroxyl radicals, which are highly reactive, nonselective and having an oxidation potential of 2.8 eV, so they can drive the oxidative degradation of a wide range of organic dye and pharmaceutical compounds, proceeding toward mineralization to carbon dioxide and water only when reaction conditions and treatment time are sufficient, and typically via intermediate transformation products along the way [25,28]. The most commonly used photocatalysts are TiO_2 and ZnO, which are chemically stable, non-toxic, inexpensive, and easily produced by wet-processing and sputtered film processing, respectively; however, they suffer from very fast electron-hole recombination and, for TiO_2, from activity limits to the ultraviolet spectral region of the solar radiation [46,77]. In recent years, heterojunction devices in which a semiconductor material like TiO_2 has been intimately connected with another such material of different band gap, such as ZnO, tin oxide or graphitic carbon nitride, have emerged as the more straightforward means of curbing recombination and, in some cases, of extending photocatalytic activity into the visible region by creating a pathway of band alignment likely to facilitate the photogenerated charge separation [28,47]. Another type of carbon nanomaterial, graphene family materials (graphene oxide, reduced graphene oxide, and graphene quantum dots), are further material candidates that combine the properties of an electron-accepting scaffold which suppresses electron-hole recombination, and a high surface area adsorbent to pre-concentrate pollutant molecules close to the catalyst surface, while also being combined with TiO_2 [46]. Simulated-solar or halogen-lamp irradiation, with degradation efficiencies up to 90% for model dyes like Congo red and methylene blue, has been reported when working with nanocomposites degrading these pollutants within a few hours; the main operational variables affecting the degradation rate were identified as pH, dosage of the photocatalyst, and concentration of the pollutant [27,78]. A high percentage removal of the parent dye or pharmaceutical, measured by loss of colour or of the parent compound's characteristic UV-Vis absorbance, does not by itself demonstrate complete mineralization to CO_2 and water, since degradation frequently proceeds through aromatic or partially oxidized intermediates that can be equally or more toxic than the parent compound; claims of mineralization should be supported by direct measurements such as total organic carbon (TOC) or chemical

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identification of the degradation products, rather than inferred from removal percentage alone. Green-synthesized TiO_2/ZnO nano catalysts, however, prepared using plant extract-mediated reduction instead of conventional precipitation, have also been shown to have good recyclability even after repeated treatment cycles without any use of toxic reducing agents that are used for the synthesis of conventional photocatalysts [27].

Nanofiltration membranes and emerging MOF-based remediation

In addition to particulate adsorbents and photocatalysts, the use of nanostructured membranes with an active layer of nanocellulose, nanofiber or nanocomposite is increasingly being adopted for the size- and charge-selective rejection of dissolved pollutants and/or particular pathogens at a flux rate which could not be attained with conventional microfiltration media, thus complementing the adsorption- and photocatalysis-based treatment trains in an integrated water treatment plant. That high, and highly adjustable, internal surface area, however, also opens the door for MOFs as environmental remediation media: In addition to the physisorptive ability of the framework to trap pollutants, where the framework includes a photoactive or redox-active metal node, the developed system will also yield the ability to catalytically degrade pollutants within the same porous medium, the same design principle of the MOF as a catalytic platform, carrying over into the environmental area [55].

Nanoparticle release, regeneration, and secondary pollution

The sustainability case for nanomaterial-based remediation made is incomplete without also addressing what happens to the nanomaterial itself after treatment. Engineered nano adsorbents and nano catalysts can release intact nanoparticles or leach their constituent metals (e.g., Fe, Ti, Zn) into treated water, particularly under acidic conditions, high ionic strength, or in the presence of natural organic matter, and once released, they can undergo further transformation - aggregation, dissolution, sulfidation, or corona formation - in natural waters that alters their mobility, reactivity and toxicity relative to the pristine material [25,27]. Spent nano adsorbents and photocatalysts also require regeneration or disposal: magnetic recovery addresses the recovery step but not the eventual fate of a saturated or spent material, and incomplete regeneration, incineration, or landfilling of spent nano adsorbents can itself become a secondary source of metal or nanoparticle contamination. These release, transformation, and end-of-life considerations are therefore central to, rather than separate from, the sustainability claims made for nanomaterial-based remediation and should be assessed alongside removal efficiency in any life-cycle evaluation of these technologies (Table 6).

Nanotoxicology, Environmental Fate, and Regulatory Considerations

Toxicity and environmental persistence of the nanomaterials in question will ultimately need to be assessed, given the dual nature of the great surface area and small size that makes them useful for catalytic purposes, biomedical applications, etc., which can also lead to unwanted interactions with biological systems and non-target organisms [27,46]. Biologically, the toxicity of nanoparticles has been consistently correlated with generation of ROS and oxidative stress, disruption of cell-membrane integrity, immune recognition by the protein corona, and, for some compositions, release of toxic metal ions after dissolving in living cells, all at the level of the organ, tissue, cell and biomolecule, modulated by the same size, shape, surface charge and surface chemistry parameters that are engineered for functional performance. Nanoparticle size, shape and surface chemistry have also been shown, in both terrestrial and aquatic compartments, to be critical determinants of environmental bioavailability; trophic transfer along food chains and interactions with co-contaminants further increase the complexity of risk assessment relative to conventional chemical pollutants [25,27]. Interestingly, up conversion nanomaterials, MOF-based drug carriers, and metal nanomaterials all have different toxicological profiles, with each characterized by ongoing systematic review, which requires contact with a materials-specific rather than generic "nanomaterial" comprehension of the toxicology [47,78].

As it has been found that regulatory frameworks have not sufficiently kept up with the range of engineered nanomaterials already commercial, potential sources of limitation in safety evaluation data, in methodology for risk assessment, and in regulations (which is simply extrapolation of data from bulk-chemical hazard assessment) have consistently been requested in various reviews, including the one in this book [79]. These gaps differ by sector rather than being generic to "nanomaterials": pharmaceutical nanomaterials are regulated as drug products, so their characterization, exposure, and quality expectations are set within existing Good-Manufacturing-Practice (GMP) and quality-by-design frameworks, but nanoscale-specific critical quality attributes (size distribution, surface chemistry, batch reproducibility) are not always explicitly required; environmental nanomaterials fall under general chemical and water-quality regulation, where exposure assessment is complicated by a lack of routine methods to detect and quantify engineered nanoparticles in complex environmental matrices; and industrial nano catalysts are regulated primarily as occupational hazards and process chemicals, with Life-Cycle Assessment (LCA) of energy and solvent use rarely mandated. Harmonizing characterization methods, exposure-assessment protocols, and life-cycle assessment across these three regulatory contexts, rather than treating them as a single generic category, is a distinct and largely unmet challenge. Furthermore, computational nanotoxicology (material flow analysis, multimedia environmental fate modelling, physiologically based toxicokinetic modelling and quantitative nanostructure activity relationships) has developed as a scalable surrogate for experimental testing to prioritize the (very large number of) nanomaterial variants that deserve detailed experimental risk assessment [77]. In addition to responsible surface modification, more comprehensive life-cycle risk assessment processes and evolving regulatory mechanisms, so-called "safer-by-design" strategies, which take toxicological considerations into account from the materials-design stage onwards together with functional design criteria discussed throughout this review, are increasingly recommended as the most practical paradigm for reconciling demonstrated functional benefits of nanostructured materials with their potential long-term impact on humans and the environment [46].

Future Directions: Translation Challenges

Although significant advances have been made in the development of nanomaterials within the last 30 years, there are some persistent hurdles that still exist when converting the synthesis of nanomaterials developed in the laboratory to catalytic, biomedical, or environmental technology applications. Another challenge that needs to be addressed is the issue of batch-to-batch reproducibility: Although many of the wet-chemical and green-synthesis strategies presented are non-trivial, maintaining uniform material properties is a concern for pharmaceutical good-manufacturing-practice or industrial-catalyst quality-control standards and can lead to small variations in the purity of reagents/mixing rates/ambient temperatures required in the preparation of these materials upon a batch-to-batch scale-up [20,63]. Scale-up of itself is often non-linear: while the milligram scale is often best for nucleation burst formation under mixing, heat and mass-transfer regimes may be quite different at the kilogram to tonne scale needed for a catalytic process for industrial catalysis or for municipal water treatment, driving the development of continuous flow and microreactor-based nanomaterial manufacturing platforms which are already starting to emerge in nano catalyst deposition [62].

A second set of questions has to do with the environment and the economy of the production of nanoscale devices. Chemical hazard issues are directly addressed by green and biogenic synthesis routes but represent a paradox, which at best can only be resolved in the future, resulting from more systematic characterization of the phytochemical or microbial parameters underlying biogenic synthesis

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Table 6. Representative nanomaterial classes deployed in water and air remediation, target pollutant, and operative mechanism.

Nanomaterial class	Typical synthesis route	Target pollutant	Operative mechanism
Magnetic iron-oxide nano adsorbents	Aqueous co-precipitation + surface functionalization	Heavy metal ions (Pb, Cd, Cr, Cu, Ni)	Surface complexation/ion exchange; magnetic recovery
Layered double hydroxide / LDH-biochar composites	Co-precipitation onto biochar or MOF-derived scaffold	Cu (II) and related divalent metal ions	High-surface-area electrostatic and chemical adsorption
Chitosan/cellulose nanocomposites	Green/biopolymer-mediated precipitation	Heavy metals, dyes	Functional-group (amine/hydroxyl) chelation
TiO_2 / ZnO (and heterojunction) nanocomposites	Sol-gel, hydrothermal, precipitation, sputtering	Organic dyes, pharmaceuticals, air-phase VOCs	Photocatalytic generation of hydroxyl/superoxide radicals
Graphene-family / TiO_2 hybrid photocatalysts	CVD graphene growth + hydrothermal TiO_2 deposition	Water- and air-phase organic pollutants	Enhanced charge separation + adsorptive pre-concentration
MOF-based adsorbents/photocatalysts	Solvothermal / microwave MOF assembly	Heavy metals, dyes, gaseous pollutants	Pore-confined physisorption; redox-active-node photocatalysis

of nanoparticles [40,36]. Additionally, all recovery technologies for nanomaterials-based products should be as well developed as the initial synthesis and performance of the product, as demonstrated by recoverable catalysts and adsorbents, while still comparable recovery technologies exist for many of the polymeric and MOF-based platforms.

The following decades of research into nanostructured materials have three directions that stand out in particular. First, machine-learning-based materials discovery is now starting to be used in the composition screening for nanomaterial catalysts, especially for combinatorically large high-entropy alloy systems and in the prediction of nanomaterial safety [39,47], and this is expected to gain momentum in the near future for the ability to map structure-function and structure-toxicity relationships. Second, multifunctional and hybrid nanostructures combining all three application fields, namely catalytic, therapeutic and imaging capabilities, can also integrate pollutant capture capabilities within their makeup, and multifunctional, theragnostic quantum dot systems, already featured in the nano MOF composites and in a segregated form, are likely to merge the historical boundaries between these three application areas further, making the unified structure–synthesis–function perspective arrived at here more relevant than ever. A third and most fundamental aspect concerns safer-by-design synthesis, where toxicological and environmental-fate criteria are considered first-order components of the synthetic design, on equal footing with size, shape and surface functionality, and this is likely to become a standard approach to new nanomaterial development as opposed to an afterthought. [24,46,77].

Conclusion

From a series of remarkable laboratory observations, nanostructured materials have developed into a sophisticated, cross-cutting technology platform whose synthetic toolkit top-down comminution, bottom-up nucleation-and-growth chemistry, template-directed and self-assembly techniques, green/biogenic reduction, and MOF assembly is now used nearly interchangeably in drug delivery, environmental remediation, and catalysis. This review has argued that the apparent diversity of applications hides a common underlying design logic: drug loading capacity and release kinetics, pollutant adsorption capacity or photocatalytic quantum yield, and catalytic active-site density and selectivity are all directly determined by control over particle size, shape, composition, and surface chemistry established during synthesis. A more effective route to future innovation than continuing domain-siloed development is to identify and take advantage of these common design principles rather than treating each application domain as a separate body of literature. However, if the significant advantages shown in catalysis, nanomedicine, and environmental engineering are to be realized safely and sustainably at scale, the same characteristics that make nanostructured materials functionally powerful high surface reactivity and small size require equally serious and materials-specific attention to toxicity, environmental fate, and regulatory oversight.

Of the barriers discussed, three appear most urgent and most tractable in the near term, in order of priority. First, batch-to-batch reproducibility at pharmaceutical- and industrial-catalyst scale remains the single largest obstacle between a promising bench-scale synthesis and a qualified product, and is more immediately addressable, through continuous-flow and microreactor manufacturing than either regulatory harmonization or fundamental toxicological characterization. Second, the absence of routine analytical methods to detect, quantify and speciate engineered nanomaterials in complex biological and environmental matrices is a rate-limiting step for both nano safety assessment and end-of-life management of spent nano adsorbents, and should be prioritized ahead of generating further material-specific toxicity data whose interpretation depends on such methods. Third, sector-differentiated regulatory frameworks that treat pharmaceutical, environmental and industrial-catalyst nanomaterials as distinct regulatory objects, rather than a single generic "nanomaterial" category, are a longer-term but necessary condition for translating the synthesis-structure-performance design rules developed in this review into products that can be manufactured, deployed and retired safely at scale.

Credit Authorship Contribution Statement

Sujatha Gundeboiyna: Writing – review; editing, Writing – original draft, Visualization, Formal analysis, supervision

Tanzeer Ahmad Dar: Writing – review; editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization, Supervision

G. Prathibha: Writing – review; editing

Madhavi Kande: Writing – review; editing

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics Declaration

This study did not involve human participants, human subjects, personal data, or animals. Therefore, ethical approval was not required.

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