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# Recent Progress in Nanostructured Functional Materials and Their Applications

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**Abstract.** Nanostructured functional materials represent a revolutionary class of substances engineered at the atomic and molecular scale (1-100 nm) to exhibit exceptional properties not found in their bulk counterparts. Spanning the past decade, this detailed survey traces the striking advances in how such materials are prepared, analyzed, and deployed across a broadening range of uses. Our survey spans pivotal material families—metallic nanocrystals, quantum dots, atom-thin 2D layers, MOFs, COFs, and their blended architectures—underscoring how each unique framework governs property and performance.Significant breakthroughs have been achieved in synthesis techniques such as confined self-assembly, seed-mediated growth, chemical vapor deposition, and solution processing, enabling precise control over size, shape, composition, and architecture. These materials have demonstrated transformative potential across diverse fields including energy storage and conversion (batteries, supercapacitors, catalysts, photovoltaics), electronics and photonics (sensors, transistors, LEDs), environmental remediation (adsorption, catalysis, filtration), and biomedicine (drug delivery, theranostics, biosensing). Particularly noteworthy are the developments in photonically active cellulose nanocrystal filaments, biodegradable near-infrared-responsive shape memory implants, and ultra-black nanocomposites for space applications. Despite these advancements, challenges remain in scalability, reproducibility, nanotoxicity, and integration into functional devices. Future research directions focus on computational design using AI and machine learning, multifunctional smart materials, biomimicry, and sustainable nanotechnology. This review highlights how nanostructured functional materials continue to drive innovation across scientific disciplines and technological applications.

**Keywords:** *Nanomaterials, Functional Materials, Synthesis Methods, Energy Applications, Biomedicine, Catalysis, Electronics, Environmental Remediation*

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## 1 Introduction

By sculpting matter atom-by-atom into sub-100 nm architectures, researchers now orchestrate property sets that dwarf what bulk solids can deliver, heralding a new era in materials design. Shrinking dimensions spotlight quantum confinement and surface-driven phenomena, endowing these species with property suites that either supercharge or completely re-imagine the responses of their bulk relatives.For instance, gold nanoparticles display vibrant ruby-red colors due to surface plasmon resonance, a phenomenon absent in bulk gold [1]; semiconductor quantum dots exhibit size-tunable electronic properties; and single-atom-thick graphene possesses exceptional strength and electrical conductivity. The fascination with nanoscale materials dates back to Richard Feynman's visionary 1959 lecture "There's Plenty of Room at the Bottom," but it wasn't until the 1980s and 1990s that synthesis and characterization techniques advanced sufficiently to enable systematic exploration of the nanoscale world. The discovery of fullerenes in 1985, carbon nanotubes in 1991, and graphene in 2004 marked significant milestones in the evolution of nanotechnology. Nanoscale building blocks have become a shared toolkit where chemical, physical, biological and engineering insights merge, turning urgent global needs—carbon-free power, precision medicine and a greener planet—into tractable technologies.Advances in atom-level engineering and streamlined production methods have unleashed a surge of innovation in functional nanomaterials, enabling the custom design of solids whose characteristics are fine-tuned for mission-specific roles. Spanning the prior decade yet zooming in on the freshest 2–3-year wave, this account maps the accelerating evolution of nanostructured functional materials, giving centre stage to findings that have eluded earlier round-ups [1].

In this work, the latest breakthroughs in the synthesis of diverse nanomaterials, highlight their unique properties, and detail their transformative applications across a spectrum of high-impact fields will be explored. The survey will critically evaluate representative material families—metallic nano-crystals, quantum-confined dots, monolayer/thin-layer crystals, MOF lattices, COF networks, and hybrid nanocomposites—highlighting their structure–property relationships. Cutting-edge preparation protocols—wet-chemical colloids, CVD growth, and directed self-assembly—will be critically reviewed together with their performance in power devices, optoelectronic circuits, pollutant removal, and therapeutic platforms.Finally, the challenges in scalability, reproducibility, and nanotoxicity, while outlining future research directions and the immense potential of nanostructured functional materials to drive technological innovation across diverse sectors will be critically examined [3].

## 2 Key Classes of Nanostructured Functional Materials and Synthesis Advances

Functional nanomaterials exhibit extraordinary variety; current efforts shift from mere discovery toward atomic-scale tailoring of dimensions, morphology, stoichiometry, and hierarchical order.The table below summarizes the major classes of these materials and their key characteristics:

***Table 1*** *Major classes of nanostructured functional materials and their characteristics*

| | Representative Materials | Key Properties |
|---|---|---|
| *Metallic Nanoparticles* | *Au, Ag, Pt, Pd nanoparticles* | *Surface plasmon resonance, high catalytic activity* |
| *Quantum dots* | *CdSe, PbS, $CsPbX_3$ perovskite QDs* | *Size-tunable photoluminescence, high quantum yield, narrow emission peaks* |
| *Two-dimensional Materials* | *Graphene, $MoS_2$, MXenes (e.g., $Ti_3C_2T_x$)* | *High conductivity, mechanical strength, layer-dependent properties* |
| *Porous framework Materials* | *MOFs, COFs, zeolites* | *High surface area, tunable pore size, multifunctional sites* |
| *Nanocomposites* | *Polymer/MXene films, photoactive Janus nanofiber membranes* | *Synergistically enhanced mechanical properties, multifunctionality* |

### 2.1 Metallic Nanoparticles (NPs)

Metallic nanoparticles (NPs), particularly noble metals (Au, Ag, Pt, and Pd), continue to be research focal points due to their strong plasmonic effects and catalytic activities. Recent advances have progressed from simple spherical particles to the synthesis of complex morphologies such as nanorods, nanocubes, nanostars, and bipyramids. These anisotropic shapes provide tunable plasmonic absorption peaks across visible and near-infrared spectra and possess high-index facets that enhance catalytic performance. Seed-mediated growth and precise control over capping agents have been crucial to these advances. Furthermore, bimetallic and multimetallic core-shell or alloyed nanoparticles (e.g., Au-Pd, Pt-Ni) have been developed to synergistically combine properties and reduce the use of expensive precious metals. For example, three-dimensional nanoporous metallic structures can be prepared through chemical dealloying of precursor alloys (e.g., Au-Ag, Au-Cu), which exhibit excellent performance in catalysis, sensing, and energy conversion [4].

Environmentally benign preparation of zero-valent iron nanospheres taps non-toxic reducing agents, bacterial or fungal biocatalysts, and leaf/seed/bark extracts as renewable precursors (Saif et al., 2016), in which microorganisms synthesis is one of the most important methods (Table 2). Nanometric metallic grains serve a broad technology spectrum—ranging from micro-chips and sunscreen lotions to anticorrosion layers, edible wraps, and polluted-water clean-up [5]. They fuse into continuous conductive skins at temperatures far below their bulk melting threshold, eliminating solvents and enabling low-heat fabrication of micro-capacitors or printed wiring. With sizes shorter than the wavelength of visible light, these particles let light pass instead of scattering it, producing crystal-clear UV-blocking agents ideal for see-through cosmetics, varnishes, and plastic packaging [6].

***Table 2*** *Synthesis of metallic nanoparticles by different microorganisms*

| Microorganism | Type of nanoparticle | Location | Size range (nm) |
|---|---|---|---|
| Pseudomonas stutzeri | Ag | Intracellular | ~200 |
| Escherichia coli | CdS | Intracellular | 2–5 |
| Yeast MKY3 | Ag | Extracellular | 2–5 |
| Aspergillus fumigatus | Ag | Extracellular | 5–25 |
| Alfalfa sprouts | Ag | Intracellular | 2–20 |
| Sargassum wightii | Au | Extracellular | 8–12 |

### 2.2 Quantum Dots (QDs)

Quantum dots (QDs) refer to semiconductor crystallites whose excitons are quantum-confined in every spatial direction. Lead sulfide (PbS), cadmium selenide (CdSe), and indium arsenide (InAs) QDs have been extensively studied. The most significant recent advancement involves the development of perovskite quantum dots (e.g., $CsPbX_3$, where X = Cl, Br, I). These materials exhibit exceptional photoluminescence quantum yields, narrow emission peaks, and easily tunable bandgaps across the entire visible spectrum by varying halide composition. Their solution processability makes them ideal for next-generation display technologies. Cadmium-free quantum emitters—carbon-derived and graphene-based dots—are increasingly favored for their minimal toxicity and excellent biocompatibility.QD synthesis typically employs the hot injection method, involving rapid thermolysis of precursors in the presence of organic capping ligands.

Routes to CQDs are commonly framed as either “bulk-down” exfoliation or “molecule-up” construction [7]. Each route brings specific strengths and trade-offs, with the final selection guided by the intended optical or surface properties of the dots. Top-down tactics, for example, fracture millimetre-scale carbon architectures—graphite flakes, nanotube bundles, carbon fibres or soot aggregates—into nanometre-sized, light-emitting crystallites via mechanical milling, oxidative etching or electrochemical exfoliation (Xu et al., 2014). Frequently employed approaches span arc-discharge erosion, pulsed-laser ablation, electrochemical exfoliation, and wet-chemical oxidation. The primary advantage of these methods is the ability to produce CQDs with relatively uniform crystallinity, though they often require harsh conditions and complex processing steps (Magagula et al., 2022). Besides, bottom-up approaches can build CQDs from molecular precursors through various carbonization processes [8]. These methods typically employ small organic molecules or polymers as carbon sources, such as citric acid, glucose, urea, ionic liquids, or natural waste products. Bottom-up growth grants nanometre-precision over dot size, contour and surface ligands, enabling application-oriented design, while subsequent hetero-atom insertion and surface re-engineering provide extra boosts to quantum yield and targeting ability. Introducing foreign atoms—nitrogen, sulfur, phosphorus or boron—into the CQD skeleton rewrites the electronic energy landscape, yielding higher fluorescence efficiency, colour-tunable emission and stronger catalytic power [7].

CQDs possess a unique set of properties that distinguish them from other carbon nanomaterials and contribute to their widespread potential applications. The most notable feature of CQDs is their tunable fluorescence, which depends on their size, surface state, and chemical composition. Most CQDs exhibit excitation wavelength-dependent photoluminescence, meaning their emission color can change with different excitation wavelengths (Fig. 1). CQDs also exhibit excellent photostability compared to traditional organic dyes and semiconductor quantum dots. They resist photobleaching even under prolonged irradiation, making them suitable for long-term imaging applications and light-driven processes (Elugoke et al., 2020). CQDs are composed of a graphitic $sp^2$-carbon core surrounded by a disordered shell carrying carboxyl, hydroxyl, amine or carbonyl handles.This hybrid structure contributes to their unique properties—the crystalline core facilitates electron transport and quantum confinement effects, while the amorphous shell provides solubility and reactivity for further functionalization. The surface functional groups dictate CQD performance and end-use potential.Oxygen-containing functional groups enable water solubility and provide sites for chemical modification. Peripheral –

COOH, –OH, –$NH_2$ or C=O sites let the dots engage in H-bonding, charge pairing or direct covalent coupling, broadening their reach from trace sensing and catalysis to hybrid-network assembly [9]. Furthermore, CQDs exhibit interesting electronic properties derived from their quantum-confined π-electrons. They demonstrate efficient electron transfer capabilities, making them valuable for electrochemical applications including electrocatalysis, energy storage, and sensing. The electrical conductivity of CQDs can be modulated through doping and surface functionalization, with nitrogen-doped CQDs showing particularly enhanced conductivity. The electrochemical properties of CQDs have been exploited for various energy-related applications. Their large surface area, tunable electronic structure, and heteroatom doping capabilities make them effective electrocatalysts for reactions such as oxygen reduction, hydrogen evolution, and carbon dioxide reduction [9].

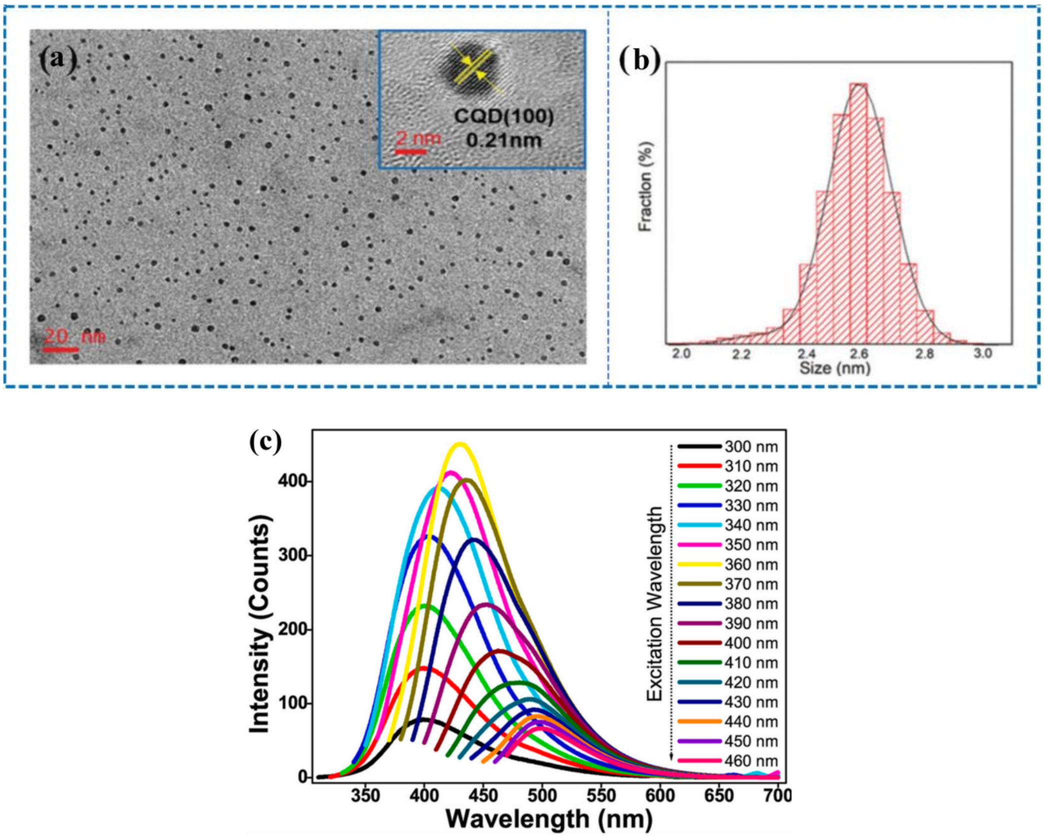


**Figure 1** Fluorescence emission spectra at different excitation wavelengths of CQDs prepared (Atchudan et al., 2022)

### 2.3 Metal-Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs)

The unveiling of crystalline frameworks whose nanoscale voids remain open to guest molecules has revolutionized materials research and engineering. MOFs and COFs stand out in this arena because their internal surface areas rival city maps, their pores can be tuned like microscope apertures, and their building blocks snap together with plug-and-play versatility [10]. MOFs, debuting in the late 1990s, knit metal ions/clusters with organic struts into 1-, 2- or 3-D lattices; COFs, arriving in 2005, ditch the heavy metals and instead weave light elements (H, B, C, N, O) into entirely covalent, all-organic scaffolds (Shah et al., 2023). The significance of these materials lies in their design flexibility and tailorable properties. MOFs offer versatility through the choice of metal nodes and organic linkers, while COFs provide exceptional stability due to their covalent connections. Both materials have demonstrated remarkable potential in various applications including catalysis, gas separation, sensing, drug delivery, and energy storage. Their ordered porous structures facilitate efficient mass transport and provide numerous active sites, making them superior to traditional porous materials in many aspects.

MOFs are typically synthesized through coordination chemistry between metal ions/clusters and organic ligands. The go-to route remains solvothermal (or hydrothermal) cooking: seal metal salts and organic linkers in a vessel with solvent, then heat under autogenous pressure to let crystals grow.This approach yields well-faceted MOF crystallites whose habit and dimensions can be dialed in by tuning temperature, solvent polarity and additive ratios.For example, the well-known Cu-BTC (HKUST-1) MOF is typically synthesized hydrothermally using copper nitrate and trimesic acid. Alternative synthesis methods have been developed to improve efficiency and control. Microwave-assisted synthesis offers reduced reaction times and improved crystal uniformity by providing rapid and homogeneous heating. Electrochemical synthesis enables the deposition of MOF films directly on electrode surfaces, facilitating their integration into devices. Mechanochemical routes simply mill the solid starting materials together, eliminating bulk solvent and markedly shrinking the environmental footprint. More recently, room-temperature synthesis methods have gained attention for their energy efficiency and simplicity [11].

COF construction relies on stitching organic monomers together via strong covalent links; because crystallinity must be achieved without the reversibility of metal–ligand coordination, the protocol is inherently more demanding than MOF synthesis. Solvothermal synthesis—sealed-vessel, high-temperature, long-duration reactions—remains the dominant COF route; the prolonged heat grants covalent bonds enough reversibility to anneal defects, directing growth toward crystalline frameworks instead of random polymer chains.Recent advances have introduced various alternative synthesis methods. Ionothermal synthesis uses ionic liquids as both solvent and template, providing unique environments for COF formation. Microwave-assisted synthesis significantly reduces reaction times from days to hours or even minutes while maintaining crystallinity. Mechanochemical synthesis offers a solvent-free approach through grinding of solid precursors. Additionally, interface-assisted synthesis (e.g., liquid-liquid or air-water interfaces) has been developed for the preparation of high-quality COF films and membranes [12].

Swappable metal nodes and linker libraries let MOFs assemble into an unrivaled spectrum of scaffold geometries. Their structures can range from one-dimensional chains to complex three-dimensional networks with multiple types of pores. The porosity of MOFs is one of their most notable features, with surface areas often exceeding 10,000 $m^2/g$. This exceptional porosity results in extraordinary adsorption capacities for various gases and molecules. COFs are characterized by their predominantly two-dimensional layered structures with periodic arrays of organic units creating well-defined pores. Although COFs typically have lower surface areas than MOFs (ranging from hundreds to thousands of $m^2/g$), they offer more uniform pore size distributions and precise pore functionality. The entirely organic composition of COFs provides advantages in terms of lower density and potentially better biocompatibility compared to MOFs [13].

Real-world utility hinges on a framework's ability to resist solvents, temperature swings, and harsh pH without collapsing.MOFs often face challenges with hydrolytic stability due to the lability of coordination bonds, particularly in aqueous or humid environments. The metal ions in MOFs are prone to hydrolysis, which can lead to framework degradation. Framework durability can be upgraded orders of magnitude by locking high-valent metals ($Zr^{4+}$, $Al^{3+}$, $Ti^{4+}$) into rigid, multi-dentate linkers, generating MOFs that stay porous in boiling water, strong acids or caustic bases. COFs generally demonstrate superior chemical stability compared to MOFs, particularly in aqueous environments, due to the strength of their covalent bonds. They exhibit stability across a wide range of conditions including organic solvents, acidic and basic solutions, and oxidizing environments. This enhanced stability makes COFs particularly attractive for applications in harsh chemical environments or where long-term stability is required [14].

The electronic properties of MOFs and COFs have received increasing attention for energy-related applications. MOFs can exhibit interesting electronic behavior depending on their metal nodes and organic linkers. Some MOFs show semiconducting properties with band gaps tunable through component selection and functionalization. Embedded metal nodes give MOFs intrinsic electron-transfer sites, turning the lattice into a tunable redox platform for batteries, supercaps and electrocatalysis. COFs typically exhibit insulating behavior but can be designed to have semiconducting properties through careful selection of building blocks and conjugation pathways. The entirely organic nature of COFs allows for precise tuning of their electronic structure through molecular design, making them promising for optoelectronic applications. Both MOFs and COFs can display luminescence from their organic components or metal centers, which can be exploited for sensing applications [15].

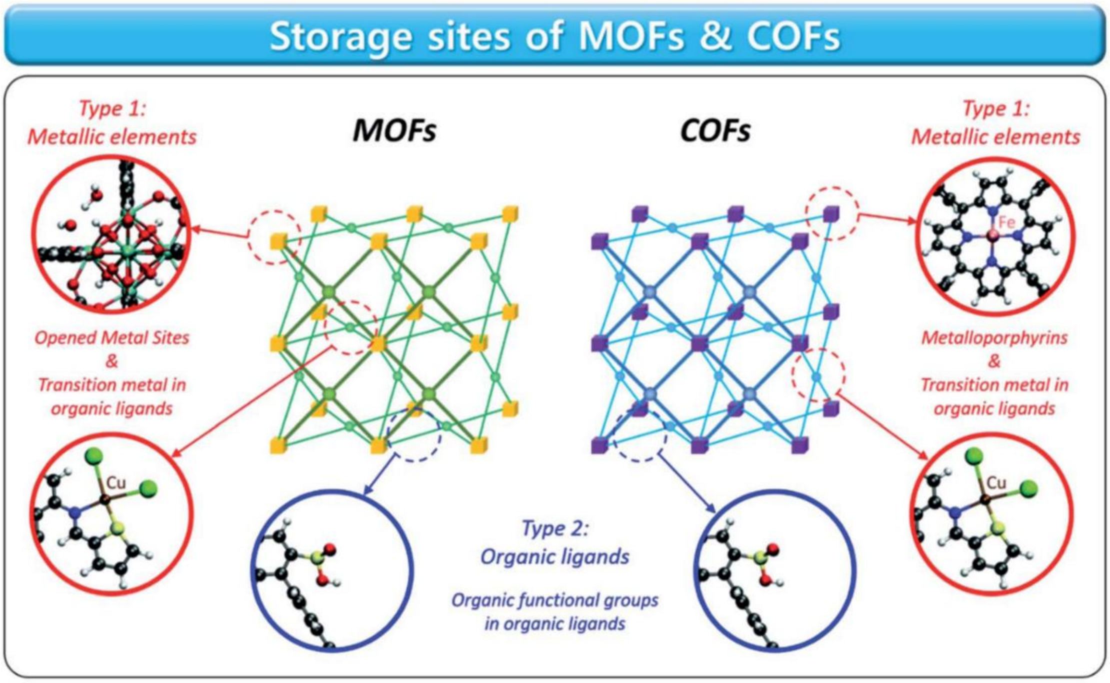


**Figure 2** Storage site exhibited by MOFs and COFs for energy storage (Teffu et al., 2025)

### 2.4 Nanocomposites and Hierarchical Structures

Integrating different nanomaterials into composites and hierarchical structures can create synergistic effects and enhanced functionalities. For example, researchers have developed a roll-to-room assisted scraping coating combined with interfacial bridging strategy to prepare high-performance MXene nanocomposite films. This approach inhibits the capillary contraction of MXene nanosheets during drying through ordered interfacial bridging, achieving regular compact assembly. The resulting bridged MXene films exhibit record tensile strength (755 MPa), toughness (17.4 MJ $m^{-3}$), and excellent electromagnetic shielding performance, while showing potential in bone regeneration applications. Another notable example is the development of photoactive Janus nanofiber membranes. By electrospinning in two steps, a Janus membrane is created: one surface is rendered water-loving and embedded with nitrogen-doped carbon quantum dots, while the opposing side forms a water-repelling micro-channel scaffold. This biomimetic structure (mimicking cactus spines and pollen) enables unidirectional water transport, efficient aerosol filtration (over 99.59% retention of PM0.3), and pathogen inactivation under UV light activation (99.9999% bacterial inactivation within 30 minutes).

## 3 Applications of Nanostructured Functional Materials in Energy Storage

The unique properties of nanostructured functional materials have enabled transformative applications across numerous fields. This section details their latest advancements in energy, electronics and photonics, biomedicine, and environmental remediation.

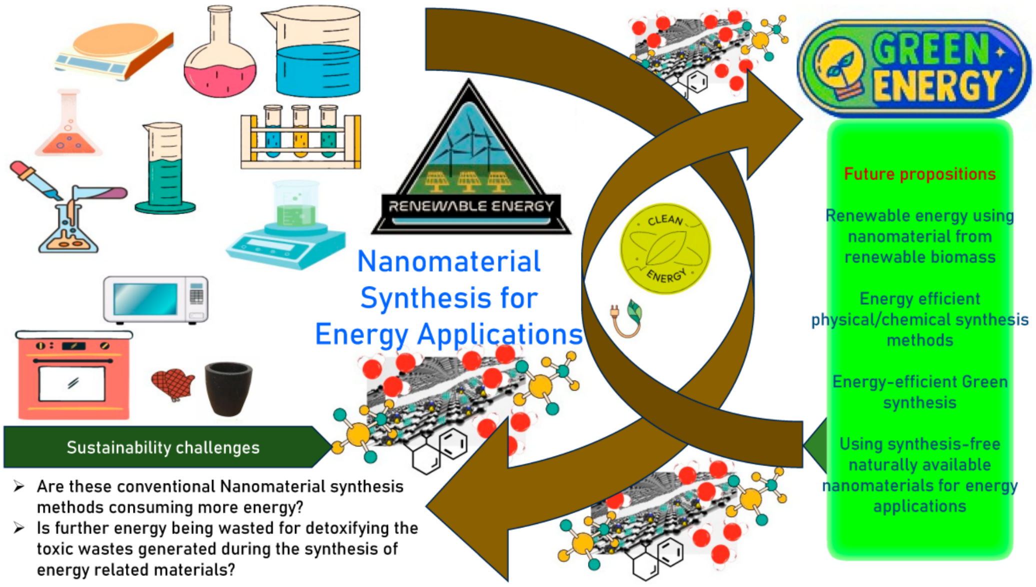
### 3.1 Lithium-Ion Batteries

Within Li-ion cells, nano-architectured electrodes deliver enlarged interfaces that multiply $Li^+$ insertion sites and slash solid-state diffusion distances for both ions and electrons. This enables higher power densities and faster charging capabilities. For anode materials, silicon nanoparticles and nanowires can theoretically store up to ten times more energy than traditional graphite anodes, addressing the critical need for higher energy density [16].

Nanocoatings play a vital role in enhancing battery durability. Protective nanoscale layers (e.g., $Al_2O_3$, $TiO_2$) applied to electrode materials prevent undesirable side reactions and structural degradation during charge-discharge cycles, significantly extending battery lifespan. Furthermore, nanostructured conductive additives such as carbon nanotubes and graphene enable more efficient electron transport throughout the electrode matrix, reducing internal resistance and improving rate capability. Recent advances include the development of multifunctional nanocomposites that combine energy storage with other properties. For example, materials with integrated thermal management capabilities help address safety concerns, while self-healing nanomaterials can repair damage that occurs during cycling, further extending battery life.

***Table 3*** *Nanomaterials in Lithium-Ion Battery Components*

| Battery Component | Conventional Material | Nanomaterial Alternatives | Key Advantages | Challenges |
|---|---|---|---|---|
| Anode | Graphite | Silicon nanoparticles, Tin oxide nanowires, Graphene composites | Higher capacity (10x), Better rate capability | Volume expansion, SEI instability |
| Cathode | $LiCoO_2$, $LiFePO_4$ | Li-rich layered oxides nanoparticles, Olivine nanophosphates | Higher voltage, Capacity, Safety | Synthesis complexity, Cost |
| Separator | Polyolefin membranes | Nanofiber composites, Ceramic nanoparticle coatings | Better thermal stability, Ionic conductivity | Thickness control, Mechanical properties |
| Current Collector | Copper, Aluminum foil | Nanostructured carbon papers, Graphene films | Lightweight, Corrosion resistance | Electrical conductivity, Cost |



- Are these conventional Nanomaterial synthesis methods consuming more energy?
- Is further energy being wasted for detoxifying the toxic wastes generated during the synthesis of energy related materials?

**Figure 3** Birds eye perspective of current challenges in energy efficient nanomaterial synthesis and future recommendations (Hasan et al., 2025)

### 3.2 Supercapacitors

Supercapacitors benefit tremendously from nanomaterials due to their reliance on surface phenomena for charge storage. Nanostructured electrodes with extremely high specific surface area (often exceeding 1000 $m^2/g$) provide more sites for electrostatic ion accumulation in electric double-layer capacitors (EDLCs). Activated carbon nanograins, graphene sheets and carbon nanotubes rule the domain thanks to superior conductivity coupled with electrochemical robustness. For pseudocapacitive materials, nanotechnology enables enhanced performance through several mechanisms. Nanoscale thickness in materials like MXenes and conducting polymer nanostructures ensures full utilization of redox-active sites and faster reaction kinetics due to shortened ion diffusion paths. The design of hybrid nanostructures that combine EDLC materials with pseudocapacitive components in a single integrated electrode has led to devices that combine high energy density with high power density. Recent breakthroughs include the development of asymmetric and battery-type hybrid supercapacitors that use nanomaterials to bridge the performance gap between traditional capacitors and batteries. These devices often feature nanostructured battery-type electrodes paired with capacitive electrodes, achieving energy densities approaching those of batteries while maintaining the power density and cycle life of supercapacitors [17].

### 3.3 Hydrogen Storage and Fuel Cells

Nano-engineered architectures unlock new strategies for packing, releasing and activating hydrogen in next-gen storage and fuel-cell systems.For hydrogen storage, nanostructured materials with high surface areas and tunable pore geometries provide enhanced physisorption capacities, while nanoconfinement of complex hydrides can alter thermodynamics and kinetics to enable reversible storage at more moderate temperatures and pressures. MOFs and COFs—crystalline scaffolds whose pores are blueprinted atom-by-atom—let designers tune hydrogen capacity by dialing in exact aperture sizes, maximizing surface area, and grafting in binding sites that catch $H_2$ without strangling release kinetics. Recent work has demonstrated that nanoscale engineering of these materials can push hydrogen storage capacities closer to practical targets for mobile applications. In fuel cells, nanostructured catalysts dramatically increase the efficiency of electrochemical reactions while reducing the loading of precious metals. Carbon-supported Pt nanograins still set the ORR performance bar, yet intense effort now targets nanostructured substitutes—transition-metal nitrides/carbides and heteroatom-doped carbons—that slash or scrap noble-metal loadings while keeping activity intact. The development of nanostructured membranes for fuel cells has also advanced significantly. Nanocomposite membranes incorporating inorganic nanoparticles within polymer matrices show improved proton conductivity, mechanical stability, and reduced fuel crossover compared to conventional materials [18].

## 4 Applications in Water Treatment

Nanostructured functional materials have transformed water treatment technologies by enabling more efficient, selective, and multifunctional approaches to contaminant removal, disinfection, and purification.

### 4.1 Adsorption and Removal of Contaminants

Nano-adsorbents boasting vast surface-to-volume ratios and switchable surface functionality have transformed conventional sorption into a precision separation platform. CNT meshes, graphene oxide sheets and activated carbon nanograins all deliver outsized uptake of heavy metals, organics and pathogens, turning water remediation into a high-rate, low-energy process.The adsorption mechanisms vary based on nanomaterial properties and target contaminants. CNTs bind organics, heavy-metal ions and dyes with record capacity, relying on π-π stacking, charge attraction, H-bonding and hydrophobic capture working alone or in concert.Their tunable surface chemistry allows functionalization for enhanced selectivity toward specific contaminants. Brief acid or plasma oxidation grafts –COOH, –OH and –C=O sites onto CNT walls, turning the tubes into ion-exchange sponges that chelate $Pb^{2+}$, $Cd^{2+}$, $Hg^{2+}$ with far higher capacity than pristine graphene cylinders.

Nanoscale iron, titanium, and aluminum oxides remove toxic metals by combining surface chelation, pH-triggered precipitation, and in-situ redox chemistry in one low-dose step.Nanoscale zerovalent iron (nZVI) particles not only adsorb contaminants but also participate in reductive degradation of pollutants such as chlorinated organic compounds and toxic metals like chromium(VI) .Emerging two-dimensional materials like MXenes and layered double hydroxides (LDHs) offer unique advantages for water treatment due to their rich surface chemistry, hydrophilicity, and tunable interlayer spacing that can be optimized for specific contaminant removal [19].

***Table 4*** *Nanomaterials for Water Contaminant Removal*

| Nanomaterial | Target Contaminants | Removal Mechanisms | Advantages |
|---|---|---|---|
| Carbon Nanotubes (CNTs) | Heavy metals, Organic dyes, Pharmaceuticals | Adsorption, Electrostatic interaction | High surface area, Tunable chemistry |
| Graphene Oxide | Heavy metals, Radioactive ions, Dyes | Adsorption, Ion exchange | Oxygen functional groups, Excellent dispersion |
| Metal Oxide Nanoparticles | Arsenic, Lead, Chromium, Fluoride | Adsorption, Precipitation, Redox | High affinity for specific metals |
| MXenes | Heavy metals, Organic pollutants, Radionuclides | Adsorption, Electrostatic interaction | Rich surface chemistry, Conductivity |
| Zeolite Nanocrystals | Ammonium, Heavy metals, Radioactive ions | Ion exchange, Adsorption | Crystalline porosity, Selectivity |

### 4.2 Membrane and Filtration Technologies

Nanostructured materials have enabled significant advances in membrane technology for water purification. Nanocomposite membranes incorporate functional nanomaterials into polymeric matrices to enhance performance characteristics including permeability, selectivity, fouling resistance, and mechanical strength. Thin-film nanocomposite (TFN) membranes incorporate nanomaterials such as zeolite nanoparticles, carbon nanotubes, or MXene nanosheets within the active layer to create enhanced transport pathways while maintaining selective properties . These membranes raise water throughput yet keep contaminant rejection intact, breaking the classic permeability-selectivity compromise.Electrospun nanofiber membranes present another architectural approach to nanotechnology-enabled water treatment. These membranes feature interconnected pore structures with high porosity and specific surface area, enabling high flux and efficient capture of contaminants. Surface functionalization of nanofibers with responsive polymers or functional groups can create membranes with stimuli-responsive properties or enhanced selectivity for target contaminants. Nanostructured ceramic membranes incorporating nanomaterials such as $TiO_2$ nanoparticles or carbon nanomaterials offer advantages in harsh operating conditions where polymeric membranes would fail. These membranes exhibit excellent chemical stability, thermal resistance, and mechanical strength while providing nanoscale control over separation properties [20].

### 4.3 Photocatalytic Degradation and Advanced Oxidation

Photocatalytic processes using nanomaterials provide an advanced approach to degrading organic pollutants that are difficult to remove by conventional methods. Semiconductor nanomaterials such as $TiO_2$, ZnO, and $WO_3$ nanoparticles can generate reactive oxygen species (ROS) under appropriate light irradiation, leading to the breakdown of organic contaminants into harmless products . The nanoscale dimensions of these photocatalysts provide several advantages: (1) increased surface area for reaction sites, (2) quantum confinement effects that tune band gap energies, and (3) reduced charge carrier migration distances to surfaces, decreasing recombination losses . Doped and modified semiconductor nanomaterials extend light absorption into the visible spectrum, making solar-driven photocatalysis more feasible for practical applications. Heterostructured nanomaterials that combine multiple semiconductors or semiconductor-metal combinations enable more efficient charge separation through engineered band alignments. For example, $TiO_2$-graphene nanocomposites demonstrate enhanced photocatalytic activity due to graphene's role as an electron acceptor that suppresses charge recombination while providing additional adsorption sites . Recent innovations include the development of nanoscale responsive materials that can be activated by alternative energy sources such as ultrasound (sonocatalysis) or electrical energy (electrocatalysis), expanding the range of conditions under which advanced oxidation processes can be effectively deployed [21].

### 4.4 Disinfection and Antimicrobial Applications

Nanostructured materials offer novel approaches to water disinfection through both reactive and non-reactive mechanisms. Nano-silver acts as a wide-range biocide, shedding $Ag^+$ that perforates cell envelopes and blocks vital biochemical steps.

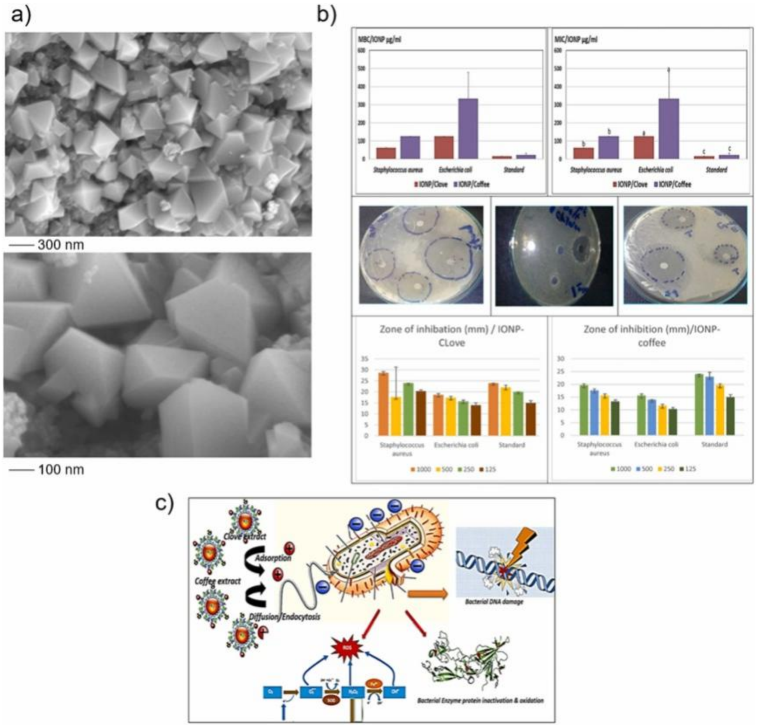


**Figure 4** Pyramidal Fe NPs; b) antibacterial activity of Fe NPs; and c; mechanism of antibacterial activity (Nyabadza et al., 2024)

Photocatalytic nanomaterials like $TiO_2$ and ZnO nanoparticles provide chemical-free disinfection through generation of reactive oxygen species that damage microbial cells. These materials offer the advantage of continuous action without consumable chemicals, though they require light activation. Carbon-based nanomaterials including graphene oxide and carbon nanotubes exhibit intrinsic antimicrobial activity through physical mechanisms such as membrane disruption, oxidative stress, and electron withdrawal [22]. Their two-dimensional structure enables effective contact with microbial cells, enhancing their disinfection efficiency. Recent advances have focused on developing nanostructured filtering systems that combine physical filtration with antimicrobial activity. These systems often incorporate multiple functional nanomaterials to address different types of microorganisms while providing redundant removal mechanisms for enhanced reliability [23].

## 5 Conclusion

The field of nanostructured functional materials continues to be a powerful engine for innovation, driven by the relentless pursuit of controlling matter at its most fundamental level. Lately, material labs have churned out an expanding toolbox—branched metal nanocrystals, glowing perovskite dots, metallic MXene sheets and hole-riddled MOFs—each cooked up with unprecedented precision. These materials are no longer mere scientific curiosities; they are enabling components of transformative technologies in sustainable energy, high-performance computing, environmental protection, and personalized medicine.

Despite persistent challenges in scalability, safety, and integration, the research trajectory is overwhelmingly positive. The convergence of nanotechnology with fields like artificial intelligence, robotics, and biotechnology promises to unlock even greater potential. As our understanding and control of the nanoscale world deepens, nanostructured functional materials are poised to redefine the future technological landscape, offering solutions to society's most pressing challenges.

## References

[1] Atchudan, R., Kishore, S.C., Gangadaran, P., Edison, T., Perumal, S., Rajendran, R.L., Alagan, M., Al-Rashed, S., Ahn, B.C., Lee, Y.R., 2022. Tunable fluorescent carbon dots from biowaste as fluorescence ink and ima ging human normal and cancer cells. Environmental Research 204https://doi.org/10.1016/j.envres.2021.112365

[2] Azeez, L., Lateef, A., Olabode, O., 2023. An overview of biogenic metallic nanoparticles for water treatme nt and purification: the state of the art. Water Sci. Technol. 88(4), 851-873. https://doi.org/10.2166/wst.2023.255

[3] Dager, A., Baliyan, A., Kurosu, S., Maekawa, T., Tachibana, M., 2020. Ultrafast synthesis of carbon quantu m dots from fenugreek seeds using microwave plasma enhanced decomposition: application of C-QDs to grow fluorescent protein crystals. Sci. Rep. 10(1)https://doi.org/10.1038/s41598-020-69264-9

[4] De Hoon, I., Barras, A., Swebocki, T., Vanmeerhaeghe, B., Bogaert, B., Muntean, C., Abderrahmani, A., Bou kherroub, R., De Smedt, S., Sauvage, F., Szunerits, S., 2023. Influence of the Size and Charge of Carbon Qu antum Dots on Their Corneal Penetration and Permeation Enhancing Properties. Acs Applied Materials & Interfaces 15(3), 3760-3771. https://doi.org/10.1021/acsami.2c18598

[5] Elugoke, S.E., Adekunle, A.S., Fayemi, O.E., Mamba, B.B., Sherif, E.M., Ebenso, E.E., 2020. Carbon-Based Q uantum Dots for Electrochemical Detection of Monoamine Neurotransmitters-Review. Biosensors-Basel 1 0(11)https://doi.org/10.3390/bios10110162

[6] Giordano, M.G., Seganti, G., Bartoli, M., Tagliaferro, A., 2023. An Overview on Carbon Quantum Dots Opti cal and Chemical Features. Molecules 28(6)https://doi.org/10.3390/molecules28062772

[7] Hasan, N., Muthu, M., Hakami, O., Gopal, J., 2025. Assessing the Sustainability of Energy-Related Nanoma terial Synthesis: Emphasizing the Need for Energy-Efficient Nanomaterial Preparation Techniques. Energie s 18(3)https://doi.org/10.3390/en18030523

[8] Iranifam, M., 2024. MOFs-, COFs- and MOGs-assisted chemiluminescence methods. Microchemical Journ al 199https://doi.org/10.1016/j.microc.2024.110096

[9] 9. Kamal, A., Hong, S., Ju, H., 2025. Carbon Quantum Dots: Synthesis, Characteristics, and Quenching as Bi ocompatible Fluorescent Probes. Biosensors-Basel 15(2)https://doi.org/10.3390/bios15020099

[10] Magagula, L.P., Masemola, C.M., Ballim, M.A., Tetana, Z.N., Moloto, N., Linganiso, E.C., 2022. Lignocellulo sic Biomass Waste-Derived Cellulose Nanocrystals and Carbon Nanomaterials: A Review. International Jou rnal of Molecular Sciences 23(8)https://doi.org/10.3390/ijms23084310

[11] Nakatani, R., Irie, T., Das, S., Fang, Q.R., Negishi, Y., 2025. Converging the Complementary Traits of Metal-Organic Frameworks and Covalent Organic Frameworks. Acs Applied Materials & Interfaces 17(17), 24701-24729. https://doi.org/10.1021/acsami.4c21991

[12] Nyabadza, A., Makhesana, M., Plouze, A., Kumar, A., Ramirez, I., Krishnamurthy, S., Vazquez, M., Brabazo n, D., 2024. Advanced nanomaterials and dendrimers in water treatment and the recycling of nanomateri als: A review. J. Environ. Chem. Eng. 12(3)https://doi.org/10.1016/j.jece.2024.112643

[13] Saif, S., Tahir, A., Chen, Y., 2016. Green Synthesis of Iron Nanoparticles and Their Environmental Applicati ons and Implications. Nanomaterials (Basel, Switzerland) 6(11)https://doi.org/10.3390/nano6110209

[14] Shah, R.H., Ali, S., Raziq, F., Ali, S., Ismail, P.M., Shah, S.Y., Iqbal, R., Wu, X.Q., He, W.D., Zu, X.T., Zada, A., Adnan, Mabood, F., Vinu, A., Jhung, S.H., Yi, J.B., Qiao, L., 2023. Exploration of metal organic frameworks and covalent organic frameworks for energy-related applications. Coordination Chemistry Reviews 477https://doi.org/10.1016/j.ccr.2022.214968

[15] Subedi, S., Rella, A.K., Trung, L.G., Kumar, V., Kang, S.W., 2022. Electrically Switchable Anisometric Carbon Quantum Dots Exhibiting Linearly Polarized Photoluminescence: Syntheses, Anisotropic Properties, and F acile Control of Uniaxial Orientation. Acs Nano 16(4), 6480-6492. https://doi.org/10.1021/acsnano.2c00758

[16] effu, D.M., Makgopa, K., Somo, T.R., Ratsoma, M.S., Honey, S., Makhado, E., Modibane, K.D., 2025. Metal and covalent organic frameworks (MOFs and COFs): A comprehensive overview of their synthesis, characterization and enhanced supercapacitor performance. Coordination Chemistry Reviews 540https://doi.org/10.1016/j.ccr.2025.216798

[17] Thakkar, K.N., Mhatre, S.S., Parikh, R.Y., 2010. Biological synthesis of metallic nanoparticles. Nanomedicine-Nanotechnology Biology and Medicine 6(2), 257-262. https://doi.org/10.1016/j.nano.2009.07.002

[18] Wang, J., Li, N., Xu, Y.X., Pang, H., 2020. Two-Dimensional MOF and COF Nanosheets: Synthesis and Applications in Electrochemistry. Chemistry-a European Journal 26(29), 6402-6422. https://doi.org/10.1002/chem.202000294

[19] Xu, Y.H., Liu, J.Q., Gao, C.L., Wang, E.K., 2014. Applications of carbon quantum dots in electrochemiluminescence: A mini review. Electrochemistry Communications 48, 151-154. https://doi.org/10.1016/j.elecom.2014.08.032

[20] Atchudan, R., Kishore, S.C., Gangadaran, P., Edison, T., Perumal, S., Rajendran, R.L., Alagan, M., Al-Rashed, S., Ahn, B.C., Lee, Y.R., 2022. Tunable fluorescent carbon dots from biowaste as fluorescence ink and imaging human normal and cancer cells. Environmental Research 204https://doi.org/10.1016/j.envres.2021.112365

[21] Hasan, N., Muthu, M., Hakami, O., Gopal, J., 2025. Assessing the Sustainability of Energy-Related Nanomaterial Synthesis: Emphasizing the Need for Energy-Efficient Nanomaterial Preparation Techniques. Energies 18(3)https://doi.org/10.3390/en18030523

[22] Nyabadza, A., Makhesana, M., Plouze, A., Kumar, A., Ramirez, I., Krishnamurthy, S., Vazquez, M., Brabazon, D., 2024. Advanced nanomaterials and dendrimers in water treatment and the recycling of nanomaterials: A review. J. Environ. Chem. Eng. 12(3)https://doi.org/10.1016/j.jece.2024.112643

[23] Teffu, D.M., Makgopa, K., Somo, T.R., Ratsoma, M.S., Honey, S., Makhado, E., Modibane, K.D., 2025. Metal and covalent organic frameworks (MOFs and COFs): A comprehensive overview of their synthesis, characterization and enhanced supercapacitor performance. Coordination Chemistry Reviews 540https://doi.org/10.1016/j.ccr.2025.216798