ACS NANO

Editors' Choice

www.acsnano.org

NANO FOCUS

33 Unresolved Questions in Nanoscience and Nanotechnology

Chad A. Mirkin,* Sarah Hurst Petrosko, Natalie Artzi, Koray Aydin, Austin Biaggne, C. Jeffrey Brinker, Katherine E. Bujold, Y. Charles Cao, Rachel R. Chan, Chaojian Chen, Peng-Cheng Chen, Xiaodong Chen, Olivier J. G. L. Chevalier, Chung Hang Jonathan Choi, Richard M. Crooks, Vinayak P. Dravid, Jingshan S. Du, Sasha B. Ebrahimi, Hongyou Fan, Omar K. Farha, C. Adrian Figg, Tanner D. Fink, Connor M. Forsyth, Harald Fuchs, Franz M. Geiger, Nathan C. Gianneschi, Kyle J. Gibson, David S. Ginger, SiShi Guo, Justin S. Hanes, Liangliang Hao, Jin Huang, Bryan M. Hunter, Fengwei Huo, Jeongmin Hwang, Rongchao Jin, Shana O. Kelley, Thomas J. Kempa, Youngeun Kim, Sergej Kudruk, Sneha Kumari, Kaitlin M. Landy, Ki-Bum Lee, Noel J. Leon, Jun Li, Yuanwei Li, Zhiwei Li, Bin Liu, Guoliang Liu, Xiaogang Liu, Luis M. Liz-Marzán, Jochen H. Lorch, Taokun Luo, Robert J. Macfarlane, Jill E. Millstone, Milan Mrksich, Catherine J. Murphy, Rajesh R. Naik, Andre E. Nel, Christopher Oetheimer, Jenny K. Hedlund Orbeck, So-Jung Park, Benjamin E. Partridge, Nicholas A. Peppas, Michelle L. Personick, Arindam Raj, Namrata Ramani, Michael B. Ross, Stacey Barnaby Ross, Edward H. Sargent, Tanushri Sengupta, George C. Schatz, Dwight S. Seferos, Tamar Seideman, Soyoung Eileen Seo, Bo Shen, Wooyoung Shim, Donghoon Shin, Ulrich Simon, Andrew J. Sinegra, Peter T. Smith, Alexander M. Spokoyny, Peter J. Stang, Alexander H. Stegh, J. Fraser Stoddart, Dayne F. Swearer, Weihong Tan, Michelle H. Teplensky, C. Shad Thaxton, David R. Walt, Mary X. Wang, Zhe Wang, Wei David Wei, Paul S. Weiss, Peter H. Winegar, Younan Xia, Yi Xie, Xiaoyang Xu, Peidong Yang, Yiming Yang, Zihao Ye, Kuk Ro Yoon, Cuizheng Zhang, Hua Zhang, Ke Zhang, Liangfang Zhang, Xiaoyu Zhang, Ye Zhang, Zijian Zheng, Wenjie Zhou, Shengshuang Zhu, and Wei Zhu

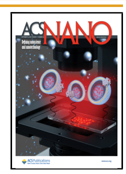
Cite This: *ACS Nano* 2025, 19, 31933−31968

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: **Significant advances in science and engineering often emerge at the intersections of disciplines. Nanoscience and nanotechnology are inherently interdisciplinary, uniting researchers from chemistry, physics, biology, medicine, materials science, and engineering. This convergence has fostered novel ways of thinking and enabled the development of materials, tools, and technologies that have transformed both basic and applied research, as well as how we address critical societal challenges. In this Nano Focus, we pose and explore 33 questions whose answers could profoundly impact fields such as energy, electronics, the environment, optics, and medicine. These questions highlight the need for deeper foundational understanding, improved tools and techniques, and innovative applications—each with significant societal relevance. Together, they represent a global call-to-action for the scientific community.**

Published: September 4, 2025



Nanoscience and nanotechnology have perhaps done more than many other modern disciplines to unite researchers across chemistry, physics, materials science, biology, engineering, and medicine (Figure 1). Originally pioneered by physicists, the field saw early

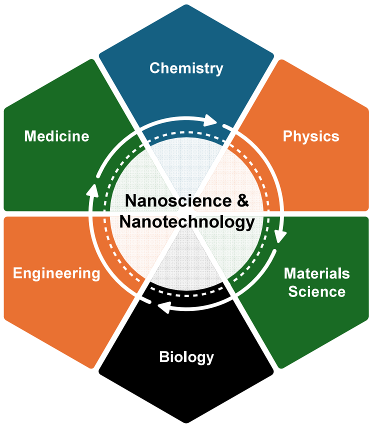


Figure 1. Nanoscience and nanotechnology have united disciplines.

breakthroughs in preparing and characterizing materials at the nanoscale—for instance, the 1986 Nobel Prize in Physics recognized the invention of the scanning tunneling microscope and the electron microscope.[1]

By the 1990s, chemists joined the field in large numbers. The 1996 Nobel Prize in Chemistry, awarded for the discovery of fullerenes,[2] transformed our understanding of carbon, arguably the most important element in the Periodic Table, and sparked further discoveries such as of carbon nanotubes and graphene. This transdisciplinary approach established a model for innovation that fields like synthetic biology and artificial intelligence (AI) are now emulating. Today, nanoscience and nanotechnology tools are integral to disciplines ranging from chemistry to engineering and medicine, continuing to drive scientific, technological, and societal (*e.g.*, policy, education, intellectual property) advancement; these fields have also been important in connecting the scientific community to the lay public.

Looking forward, nanoscience and nanotechnology are well-positioned to address critical global challenges. In this Nano Focus, we present 33 questions—each accompanied by an answer—designed to foster cross-disciplinary dialogue and collaboration. The number of questions corresponds to the number of years of the existence of one of our laboratories (C. A. M.) at the time this project was initiated, a hub of extensive and collaborative research efforts, and also closely coincides with the number of years since many foundational papers in nanoscience and technology appeared in print. The Mirkin lab at Northwestern University (NU) was established in 1991, and NU also hosts the International Institute for Nanotechnology (IIN), founded in 2000, which has grown into one of the world's largest centers for nanoscience research and education. This dynamic research and training environment has significantly contributed to the sustained growth of the field, having contributed to the education of hundreds of faculty members now leading research programs at top institutions worldwide, including many authors of this Nano Focus.

We have organized the 33 questions and responses according to the framework proposed by the Chemical Abstracts Service (CAS) of the American Chemical Society (ACS),[3] which classifies Nobel Prize-recognized innovation into three categories: (1) Foundational Understanding (11 questions), (2) Tools and Techniques (7 questions), and (3) Impactful Applications (11 questions) (Figure 2). Additionally, we explore four questions related to the societal implications of nanotechnology. Addressing the challenges outlined in this article would lead to transformative scientific and societal progress. We offer this Nano Focus as a call-to-action—urging researchers across disciplines to come together in pursuit of integrated, collaborative solutions to some of the most complex problems of our time.

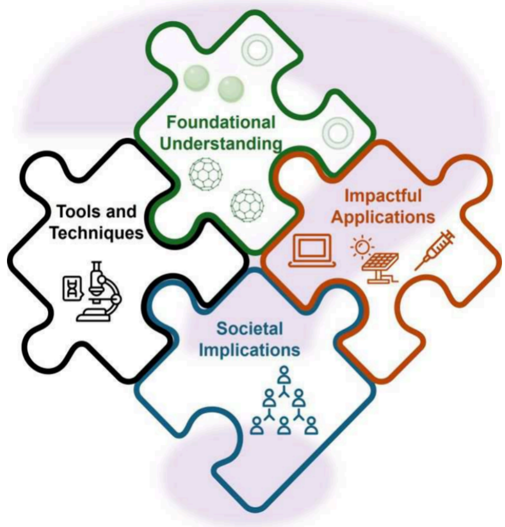


Figure 2. Key unresolved questions in nanoscience and nanotechnology encompass: Foundational Understanding, Tools and Techniques, Impactful Applications, and Societal Implications.

FOUNDATIONAL UNDERSTANDING

According to the CAS,[3] foundational understanding refers to insights from basic research that deepen our knowledge of the world. In nanoscience and nanotechnology, this targeted insight involves exploring how materials can be designed and synthesized to achieve programmable properties beyond those found in nature. Researchers aim to understand the behavior of these novel materials in complex environments. A key area of interest is reverse engineering: starting with desired properties, identifying suitable materials, and synthesizing them through chemical or top-down physical methods. An ultimate goal is to develop design principles by integrating theoretical models with experimental data. Such concepts form the basis of the discussions in this section.

DESIGNING AND SYNTHESIZING NEW FORMS OF MATTER WITH CHEMICAL PRECISION

1. When is atomic and molecular precision in nanostructure synthesis most important, and how can it be achieved? Atomic and molecular precision in nanostructure synthesis is essential when specific material properties, such as electronic, catalytic, or optical behavior, depend on well-defined structure−property relationships. This level of control is particularly important for fundamental studies aimed at understanding how nanomaterials behave under different conditions and in applications that require reproducible and high-performance materials.

Significant advances have been made. Individual atoms can be positioned on surfaces.[4−6] Hundreds of routes to atomically precise metal nanoclusters (*e.g.*, $Au_{25}(SR)_{18}$ *via* size-focusing methods) and reactions involving them exist.[7−9] Dendrimer-templated approaches enable particle uniformity without the intentional use of surface ligands.[10] The hot-injection method

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

has become foundational in synthesizing well-defined nanocrystals (2−100 nm), while ligand-assisted and electrochemical strategies provide further control over morphology and exposed facets.[11−16] Bimetallic nanostructures can also be engineered to localize specific elements, tailoring surface activity for catalysis.[17−19] These synthetic innovations have enabled hierarchical assemblies with emergent properties.[20−23] The degree of precision required depends on the application. In catalysis, parameters like oxidation state, surface facets, (crystal) phases, and adsorbates significantly affect activity.[15,19,24−28] In optics and electronics, defect structures modulate performance-critical properties such as photoluminescence and conductivity.

Despite these developments, much of the field still relies on empirical optimization. To transition toward predictive synthesis, researchers must develop a mechanistic understanding of nanostructure growth, refine thermodynamic and kinetic control, and identify critical parameters for each application. In catalysis, where active sites may form dynamically under reaction conditions, *in situ* tools capable of resolving atomic transformations are essential.[10] Current ensemble methods like X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS) must be complemented by single-particle and correlative techniques,[29] and theoretical tools such as density functional theory (DFT) and electromagnetic modeling remain invaluable. Emerging integration of machine learning (ML) and AI[30,31] offers new potential to map synthesis conditions to desired outcomes, setting the stage for the routine and automated creation and scale-up of atomically precise nanostructures.

2. What innovations are needed to make nanomaterials functional in extreme environments? Nanomaterials designed for use in extreme environments, such as high temperature, pressure, mechanical strain, or radiation or high or low pH, must maintain stability and performance despite their inherently high surface reactivity. While their tunable properties offer opportunities for enhanced performance (*e.g.*, improved catalytic activity under high pressure), these same traits can lead to structural degradation under harsh conditions.[32,33]

A critical need is for *operando* and *in situ* characterization techniques that track atomic-scale structural changes in real time. Tools like electron microscopy and X-ray spectroscopies have begun to simulate extreme conditions, but more robust methods with high spatiotemporal resolution are needed to inform stability design.[34−36] Theory has been used to develop optical control methods based on the phase, intensity, or spectral composition of light. Although researchers have applied such methods to control, and in some cases to understand, complex systems, including molecular-scale electronics, some are not practically feasible or experimentally implementable in the laboratory. In that respect, moderately intense, short-pulse laser fields have an advantage.[37] Computational approaches like DFT and molecular dynamics offer valuable insight[38−40] but often fall short due to assumptions that simplify environmental complexity.[41] Improved algorithms and integration with AI can better capture real-world conditions and expand predictive power across broader chemical spaces.

Materials innovations are also essential. High-entropy alloys (HEAs), composed of multiple metals with near-equimolar ratios, offer exceptional thermal and mechanical stability due to entropy-driven phase stabilization and sluggish diffusion.[42−44] Ceramics and ceramic matrix composites, including those composed of borides, nitrides, and carbides, exhibit extreme hardness and thermal resistance,[45,46] making them suitable for aerospace and nuclear applications. Two-dimensional (2D) materials like graphene and MoS_2 also show promise due to their flexibility, chemical inertness, and thermal conductivity.[47] Even promising materials can fail in deployment without consistent production routes. Interdisciplinary progress, merging advanced synthesis, ML-guided simulation, and real-time characterization, is key to designing nanomaterials that are not only functional but also reliable in environments far from equilibrium.

3. Given the rise of structural nanomedicine, how can we design nanomedicines with molecular precision for optimized therapeutic potency? Molecularly precise nanomedicines represent a new frontier in therapeutic design, offering control over drug identity, spatial arrangement, and hence physicochemical properties. Unlike conventional formulations or larger self-assembled structures, structural nanomedicines,[48−51] by controlling structural presentation in addition to composition, allow fine-tuning of performance metrics—such as circulation time, cellular uptake, and therapeutic potency—while minimizing toxicity.[52−62]

Uniformity is key. Precision synthesis ensures batch-to-batch reproducibility,[53,55,63−66] enabling clearer interpretation of pharmacokinetics and biological interactions. Extended circulation, often achieved through poly(ethylene glycol) (PEG)-ylation, improves bioavailability and therapeutic index.[67,68] Targeting is enhanced through surface modification, such as antibody conjugation[69−79] or physical tuning of size, charge, and shape, to navigate biological barriers like the blood−brain barrier (BBB).[80−82] Methods are needed to formulate nanoparticles as well as to measure the density and positioning of various ligands on nanoparticle surfaces, which is not always straightforward using current methodologies.

Controlled-release systems responsive to pH, enzymes, or metabolic cues enable site-specific activation, increasing efficacy while limiting systemic exposure.[83−88] Paracrine-transfer mechanisms, where particles enter one cell and are passed to neighbors, can also enable staged delivery for localized and sustained treatment.[89] Exploring broader size ranges expands application potential; smaller nanomaterials (3−10 nm) enter cells more efficiently, can engage key biological targets more selectively, penetrate tissues more deeply, and help avoid immune clearance.[90−93] Larger mimetic structures (300 nm−1 μm), such as red blood cell-mimicking carriers or membrane-coated particles, evade phagocytosis and prolong circulation.[94−99]

Next-generation structural nanomedicines will combine multiple functional agents—*e.g.*, peptides, nucleic acids, proteins, and polymers—to perform synergistic tasks.[92,93,100−104] These multicomponent systems may enable programmable responses, self-amplifying signals, or feedback-controlled delivery. Progress requires advances in *in vivo* analytics, manufacturing, and regulatory frameworks. Only with molecular-level design, standardized production, and real-time tracking will the field of structural nanomedicine fully transform therapeutic paradigms.

DELINEATING STRUCTURE−FUNCTION RELATIONSHIPS

4. How can understanding structure−function relationships in natural systems guide the design of

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

synthetic materials with enhanced functionality? To design synthetic materials that match or exceed nature's capabilities, we must first understand how biological systems use structure to control function. Natural materials like enzymes achieve near-perfect catalytic efficiencies, performing complex reactions with minimal energy loss. These biological exemplars inspire the rational design of nanostructures for applications in catalysis, energy storage, and biomedicine.

A central challenge lies in replicating dynamic, hierarchical, and adaptive functions observed in biology. Unlike rigid synthetic systems, biological structures respond to stimuli and self-regulate, offering pathways toward intelligent, self-assembling materials. Advances in structural biology, including tools that predict protein 3D structures from amino acid sequences,[105] are now being extended to biomolecule−nanomaterial systems using unified structural descriptors.[106,107] These approaches enable predictive control over nanomaterial assembly and reactivity, moving us closer to synthetic analogs of protein machines.[108]

Synthetic mimicry also involves replicating biological interfaces.[109−118] For example, hydrated silicon dioxide mimics the protective effects of water on membranes. Unlike conventional cryopreservation, nanosilicification preserves cells and tissues at ambient temperatures, protecting them from oxidation and UV degradation. Upon rehydration, the silica shell dissolves, and biological function is restored, offering a cost-effective solution for storing sensitive biological samples.

Another emerging frontier is phase-separated nanomaterials inspired by cellular compartmentalization *via* liquid−liquid phase separation. These transiently ordered systems do not rely on static structure but instead gain function through reversible organization. Such materials challenge the classical "structure defines function" paradigm, providing a foundation for adaptive nanotechnologies.

Ultimately, by learning how living matter controls function through structure, motion, and environment, researchers can engineer synthetic systems that not only mimic biology but extend it, offering new tools for sustainable energy, responsive medicine, and materials with life-like properties.[119,120]

5. How can structure−function relationships be leveraged to control charge dynamics in nanoscale systems? Understanding and exploiting structure−function relationships is key to manipulating electronic charge at the nanoscale.[121] Charge dynamics, encompassing generation, separation, motion, and recombination, govern many quantum phenomena and device functionalities. Carefully engineered materials, such as type-II heterojunctions, exploit band offsets to separate electrons and holes spatially after photoexcitation.[122] For example, lead-halide perovskite/metal oxide heterostructures facilitate directional charge transfer, enhancing photocatalytic and photovoltaic performance.[123−128] Materials discovery in this area is critical.

In addition, capturing these ultrafast events, which occur on femto- to attosecond time scales and nanometer length scales, requires advanced characterization.[129−133] Transient absorbance (TA) spectroscopy and nonlinear optical methods, such as second harmonic generation (SHG), provide femtosecond resolution and are sensitive to electric fields and excited-state dynamics. Pushing these technologies to higher spatiotemporal resolution remains critical for real-time insights into charge behavior.[134] Theory also has been a major tool in the development of ultrafast, space-resolved control and analysis of electronic behaviors. Numerically, it is straightforward to predict and to analyze electronic behaviors down to the ultimate time- and space-resolved limits because wavepacket propagation methods are improving with the efficiency of Fourier transform techniques. Additionally, semiclassical methods, which are typically useful for multidimensional systems and for describing molecules coupled to an environment, quickly become efficient.

Scanning probe techniques and high-resolution electron microscopy complement optical methods by revealing the nanoscale landscape over which charges move. Atomic-resolution imaging of charge domains, defects, and interfaces helps correlate structure with electronic function.[135−141] Enhancing *in situ* electron microscopy and enabling *operando* imaging of devices can convert these tools into ″nanolabs″ where electronic and structural evolution can be tracked simultaneously.[142]

Emerging tools like ultrafast electron microscopy (UEM) combine the time resolution of spectroscopy with the spatial resolution of electron imaging.[143−145] Similarly, electron holography can quantify electrostatic potentials at atomic resolution and assess single-particle charge states,[146,147] and time-resolved scanning tunneling microscopy, often based on plasmonics, is also important.

Together, these complementary techniques will advance our understanding of charge manipulation, enabling the precise design of nanomaterials for quantum computing, neuromorphic systems, and high-efficiency energy devices. As structure increasingly dictates electronic behavior at the nanoscale, structure−function insights will be vital to developing materials that exploit quantum phenomena with high fidelity.

SCALING AND INTEGRATING NANOMATERIALS INTO FUNCTIONAL SYSTEMS

6. How can nanomaterials be scaled and integrated into larger structures and functional devices? Once a nanomaterial with promising properties has been developed, the challenge shifts to producing it at scale and integrating it into macroscale systems. Many existing synthesis techniques, such as high-throughput nanolithographies and microfluidics, enable the creation of complex nanostructures with useful catalytic, optical, or electronic functions.[148−161] However, translating some of these types of methods to production at industrially relevant scales remains a significant hurdle.

A core issue is the inherently dilute nature of nanoparticle suspensions.[162] Producing dense solids from dilute systems requires large volumes of solvent, making the process inefficient. To overcome this challenge, researchers are developing methods that allow stable, high-concentration nanoparticle solutions while retaining control over interparticle interactions for a variety of applications, including optics.[163] Ligand design is critical because ligands not only stabilize particles but also govern assembly, interfacial behavior, and functional properties.[164−179] Building comprehensive, scalable ligand libraries, including DNA, small molecules, and synthetic polymers, is essential. Researchers in related fields have also sought to solve similar issues to increase the chemical content of metal and ceramic inks of various compositions for use in patterning and additive manufacturing.[180,181]

Processing nanoparticles into bulk materials or functional devices poses additional challenges.[155,182] While superlattices formed from nanoparticles can mimic atomic crystals, their

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

growth dynamics differ markedly due to the larger sizes and weaker forces at play.[183,184] The kinetics of these processes affect material microstructure.[185−190] While atomic solids rely on microstructural control for property management, their effects on nanoparticle assemblies remain less explored. New assembly methods must account for these mesoscale phenomena, enabling precise delivery of thermal, mechanical, or electromagnetic energy during fabrication.

Integration into devices requires maintaining nanoscale functionality within macroscale architectures. This integration might involve embedding nanoparticles in flexible substrates, 3D printing nanocomposites, or creating multiscale heterostructures. As materials are scaled, interfaces become crucial, dictating performance and failure modes. Future progress depends on understanding the multiscale thermodynamics, kinetics, and mechanics of nanostructure assembly and integration. Bridging the gap between nanoscale precision and macroscale utility will unlock transformative applications in energy systems, computing, healthcare, and structural materials.

7. How can we integrate nanoscale components and processes with larger-scale systems to create devices with hierarchical structure and function across length and time scales? Integrating nanoscale components into larger-scale systems to create functional devices with structural and temporal hierarchies remains a central challenge in nanoscience. Biological systems provide compelling models, where nanoscale machineries exhibit highly organized architectures and operate synergistically across spatial and temporal dimensions.[191,192] Mimicking such multiscale coordination in engineered systems requires precise definition of nanoscale building blocks and seamless connection across length scales.[193]

Top-down fabrication methods, such as wafer-scale photolithography, offer high spatial precision but face limitations in scalability and cost.[194] Bottom-up strategies, including the synthesis and self-assembly of nanoparticles and nanoclusters, enable complex organization from the molecular level upward.[195] A hybrid approach combining these methods is critical for constructing hierarchical structures with tailored geometries and functions.

Recent work has demonstrated controlled assembly of nanoclusters into superstructures for optical and electronic applications,[182,196−201] yet achieving arbitrary geometries with robust integration remains difficult. Advances in ML are addressing this gap by enabling predictive design across scales.[202] Inspired by protein folding breakthroughs like AlphaFold,[203,204] ML models now predict properties of atomic clusters,[205,206] metal−organic frameworks (MOFs),[207,208] and perovskites,[209,210] helping bridge nanoscale traits with macroscopic material performance (see also Question 9 below).

Temporal hierarchies are vital. Many critical nanoscale processes, such as electrocatalysis, occur over femtosecond to second time scales.[211,212] Designing devices that leverage these processes requires synchronizing kinetic and structural hierarchies.[213] This strategy motivates the development of responsive, multilength-scale architectures optimized for dynamic function.

Progress depends on advanced characterization. *In situ* and *operando* microscopies,[214] correlative techniques,[215] and ultrafast spectroscopies[216] enable simultaneous monitoring of structural and functional dynamics, providing key insights into multiscale interactions. These tools and strategies drive the rational design of integrated devices that exploit nanoscale phenomena for macroscopic utility.

8. How can nanoenabled devices be seamlessly integrated with biological systems to improve human health? Seamless integration of nanoenabled devices with biological systems holds great promise for transforming healthcare, but it requires careful attention to both materials and systems design. Recent advances in wearable and implantable nanodevices have demonstrated exciting capabilities for diagnostics, monitoring, and therapy.[217−222] However, true integration demands that devices operate harmoniously within the complex and dynamic human body as has been accomplished in certain cases with larger scale systems (*e.g.*, implantable defibrillators with batteries that last approximately 10 years and are Bluetooth-enabled and capable of communicating data to hospitals *via* an app).

Materials in direct contact with biological tissue must be biocompatible, avoiding immune responses or fibrosis, and resilient to mechanical strain over time.[223−225] Mismatches in mechanical properties between soft tissues and rigid electronics can cause damage and limit long-term stability. To address this issue, researchers are developing shape-adaptive interfaces that match the mechanical compliance of tissues, improving integration and minimizing inflammation.[226−229]

For skin-mounted devices, breathability is critical to ensure user comfort and prevent irritation. Natural materials such as silk have emerged as promising substrates due to their biocompatibility, flexibility, and gas permeability.[230−234] These innovations are key to developing unobtrusive, long-term health monitors.

Powering such miniaturized systems remains a major hurdle. Conventional batteries are bulky, rigid, and often require invasive replacement procedures.[235] Bioenergy harvesters, which convert mechanical, thermal, or biochemical energy from the body into usable electricity, represent a compelling alternative and are under active development.[236,237] On the system level, high-resolution nanosensors generate large volumes of real-time data, necessitating robust data management and wireless communication platforms.[238] Ensuring data security, processing speed, and scalability will be essential for widespread clinical use.

Ultimately, nanoenabled devices must evolve into "smart" systems that sense biological signals and autonomously respond to disease states. Integrating AI enables these devices to analyze complex data sets, personalize treatment, and enhance early detection.[239,240] These advances are reshaping how we interface electronics with the human body, paving the way for the next generation of personalized, responsive healthcare technologies.

MULTISCALE MODELING OF NANOMATERIALS

9. How can we model materials across length scales where classical or quantum mechanics alone are inadequate to match theory and experiment? Modeling materials across multiple scales—from atoms to devices—is crucial for understanding complex nanomaterial behavior, yet no single theoretical framework suffices across all regimes. Classical and quantum mechanics each provide foundational insights: quantum mechanics excels at capturing electronic properties of small systems, while classical molecular dynamics (MD) and Monte Carlo methods model larger systems using empirical or quantum-derived forces.[241] However, these

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

methods face limitations in scale, accuracy, or computational cost.[242]

For very large systems or long time scales, coarse-grained models group atoms into simplified units, or "beads," enabling simulations of polymers, DNA, proteins, and nanoparticle superlattices.[243−251] Yet, such models struggle with chemical processes like bond formation or redox reactions, especially at interfaces between dissimilar materials. At coarser levels, continuum theories are applied, but often lack the resolution needed to capture mesoscale phenomena and may be constrained by computational resources.[252−254]

To bridge these gaps, multiscale modeling approaches have emerged. Hybrid schemes, such as mixed quantum-classical or semiclassical models, are particularly effective for describing light-matter interactions. For example, finite-difference time-domain (FDTD) and finite element methods (FEM) are widely used in classical electrodynamics,[255,256] while quantum electrodynamics is necessary to understand nanoscale optical phenomena such as in quantum dots, plasmonics, and strong light-matter coupling.[257,258] Mixed and semiclassical methods provide a balance between computational efficiency and quantum accuracy.[259−262]

Both ML and AI are increasingly integrated into multiscale frameworks to accelerate simulations, improve force field accuracy, and model complex phenomena. Notable successes include protein folding predictions[203] and ML-derived interatomic potentials,[263] as well as reaction modeling.[264] These data-driven approaches can complement physics-based methods, particularly in challenging intermediate regimes where neither classical nor quantum mechanics alone are sufficient. Ultimately, combining coarse-graining, hybrid quantum-classical methods, and ML offers a path to unify theoretical and experimental understanding across scales, essential for the predictive design of next-generation nanomaterials.

UNDERSTANDING AND EXPLOITING NANOMATERIAL LIFECYCLES

10. Given that nanostructures are often dynamic under external stimuli, how can we predictably control nanoparticle durability—and can self-healing mechanisms be designed to prolong functionality? Nanostructures are inherently dynamic, responding to stimuli such as light, heat, and electrochemical input in ways that can both enhance functionality and accelerate degradation.[265,266] While this dynamism enables tunable behavior, it introduces challenges for their long-term durability, particularly in high-performance applications like energy storage, catalysis, and sensing. Designing nanoparticles that respond to repeated stimulation in a predictable and robust manner is therefore critical.

One promising strategy is to draw inspiration from biological systems, where self-repair is common. Adaptive nanostructures capable of reconfiguring or restoring their function after damage could maintain performance over extended use.[267] Such self-healing materials might incorporate built-in feedback mechanisms that detect structural failure and initiate repair without significant external input. However, the complexity of these systems makes material selection and integration of self-repair functions particularly challenging.

An equally important design consideration is end-of-life behavior. Rather than maximizing durability indefinitely, in some cases it may be desirable to enable controlled degradation after functional use. Degradable coatings or modular architectures can facilitate the recovery of valuable components and reduce environmental impact.[268−274] For instance, soft materials like nanocellulose offer built-in degradability,[275] while coordination chemistry has been used to recover gold atoms from nanoparticles using benign agents such as cyclodextrins.[276] These strategies highlight the potential to design nanoparticles not only for performance but also for sustainability and recyclability.

Ultimately, future nanostructures should balance resilience and responsiveness during their operational lifespan with environmentally and economically beneficial disassembly at end-of-life. This dual focus on durability and degradability will be essential for sustainable nanotechnology in advanced applications.

11. What are the key factors in nanometabolomics, and can we design nanometabolites to act as therapies rather than just byproducts? Nanometabolomics—the study of how nanomedicines are metabolized—plays a critical role in understanding and optimizing the safety and efficacy of nanoscale therapeutics. The pharmacokinetics (PK) and pharmacodynamics (PD) of nanomedicines depend heavily on size, shape, surface chemistry, and composition,[277−280] yet these parameters remain insufficiently characterized in many systems. Once inside the body, nanoparticles can exhibit complex and unpredictable behavior,[281] necessitating early identification and characterization of resulting nanometabolites.

To ensure safe and effective use, these nanometabolites must be examined not only for toxicity but also for therapeutic potential. This shift—from viewing nanometabolites as waste products to potentially useful agents—could open new avenues for therapy. Accurate ADME (absorption, distribution, metabolism, and excretion) profiling, integrated with physiologically based pharmacokinetic (PBPK) models, is essential for understanding *in vivo* behavior.[282,283] These models are especially useful when guided by ML, enabling prediction of nanomedicine fate from *in vitro* data.

Complexities multiply with multicomponent nanomedicines, where component interactions affect PK/PD in ways not captured by single-entity models.[61,65,284−297] These formulations require advanced, systems-level models that account for structural organization, degradation pathways, and the roles of individual components—including beneficial nanometabolites.

A key complicating factor is the formation of a "protein corona" around nanoparticles upon exposure to biological fluids.[298] This corona modulates interactions with cells and organs, profoundly affecting ADME and immune responses. Protein identification, ideally conducted *in vivo via* mass spectrometry, is vital,[299] though conventional techniques are often incompatible with soft nanomaterials.[300] Moreover, corona composition varies with administration route, patient physiology, and even lab-specific conditions, underscoring the need for standardized analytical protocols.[301,302]

Integrating mass spectrometry data with PBPK models could enable predictive mapping of protein-nanoparticle interactions to biological outcomes. Ultimately, refining nanometabolomics will not only ensure safer nanomedicines but also allow rational engineering of therapeutic nanometabolites, transforming how we design and deploy nanoscale treatments.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

TOOLS AND TECHNIQUES

Tools and techniques encompass innovations that enable new research methods, significantly enhancing or accelerating scientific progress.[3] Nanomaterials, with their unique structures and properties distinct from both molecules and bulk materials, require specialized tools for analysis. Characterization techniques have evolved alongside synthetic methods and have been essential to the field's development. Device fabrication also plays key roles in translating nanomaterials into practical applications. More recently, AI and ML have become integral to nanoscience, offering advanced solutions for data analysis, predictive modeling, and problem solving. Additionally, cross-disciplinary tools are crucial for fostering collaboration and accelerating progress. Universal platforms that operate across various materials and domains would promote greater efficiency, integration, and innovation.

DEVELOPING NEW SYNTHETIC PROTOCOLS WITH SUSTAINABILITY IN MIND

12. How can we design nanomaterial syntheses to be sustainable across raw materials, reactions, and manufacturing processes? To minimize the environmental and human health impact of nanotechnology tools, nanomaterial syntheses must embrace sustainable principles from the outset. This includes using renewable feedstocks, environmentally benign reagents, and energy-efficient methods. Green synthesis pathways should prioritize atom economy, favoring reactions that maximize the incorporation of raw materials into the final product, while minimizing waste and side products.[303−306] Lifecycle analyses should be routinely applied to evaluate environmental costs from synthesis through disposal and paired with standardized sustainability guidelines.[307] Predictive tools, such as ML, can assist by modeling the environmental and biological impacts of nanomaterials, accelerating the discovery of safer and more sustainable alternatives.[308]

Biomass-based nanomaterials—derived from abundant, biocompatible feedstocks—are particularly promising.[309−314] For example, cellulose-based materials have been employed in solar steam generation,[315] lignin-derived hydrogels in drug delivery,[316] plant polyphenols in nanolithography,[317] and protein templates in the synthesis of metal nanoparticles, quantum dots, and polymers.[318−321] Environmentally friendly reaction conditions, such as ambient temperature, aqueous solvents, microwave or ultrasound-assisted reactions, and enzyme catalysis, should continue to be explored.[322−325]

Advances in automation and high-throughput synthesis can further reduce energy consumption and increase reproducibility.[326−329] However, sustainability challenges remain, particularly with biomolecules like DNA that are frequently used in nanomaterial assembly.[71,330,331] Traditional phosphoramidite-based DNA synthesis involves toxic solvents and excessive reagents.[332] Alternatives such as enzymatic synthesis with terminal deoxynucleotidyl transferase (TdT),[333−336] improved solid-phase techniques,[337−339] and P(V)-based coupling reagents[340−342] are emerging. Sustainable syntheses of modified nucleic acids like deoxynucleic guanidines have been achieved using iodine in place of mercuric chloride.[343,344]

Ultimately, sustainability should be integrated into every stage of nanomaterial development—from molecular design and reaction conditions to manufacturing scale-up and end-of-life disposal. Making sustainable nanomaterial synthesis the default rather than the exception will require both technological innovation and cultural shifts within the research community.

DEVELOPING NEW TOOLS TO STUDY THE NANOSCALE WORLD

13. What tools are needed to study single nanomaterials and assemblies in native, dynamic environments? Conventional characterization techniques often average the properties of nanomaterials over space and time, obscuring critical insights into dynamic behavior at the single-particle level.[345] To understand nanoscale processes as they occur in real-world environments, new tools must deliver high-resolution, temporally resolved data *in situ* and *operando*.

Radiation-based approaches (*e.g.*, electron, ion, or photon probes) and scanning techniques like scanning probe microscopy (SPM) provide localized information.[346] Advanced transmission electron microscopy (TEM) now enables atomic-scale resolution, 3D tomography, and real-time studies of materials under environmental stimuli.[347−351] To realize these capabilities, multimodal platforms that integrate nanofabricated specimen stages with imaging, spectroscopy, and data analyses are needed.[352,353]

Instrumentation must continue to evolve: coherent sources, aberration correctors, high-dynamic range detectors, and encapsulated micro/nanofabricated chips allow imaging under realistic temperature, pressure, liquid, or gas conditions.[354] Innovations like *in situ* TEM stages with microfluidics and environmental controls enable direct observation of structural evolution.[355] Stimuli such as light, force, or X-rays can be applied within these systems to explore nanoscale responses. Both AI and ML are critical enablers of next-generation analysis. Integrated into tools like 4D STEM or atomic force microscopy (AFM), they enhance acquisition speed, automate processing, and improve reproducibility.[356,357] ML models trained on large data sets can detect trends, direct attention to emerging events in real time, and even adapt experimental parameters on-the-fly.

Ultimately, researchers must develop a new generation of instruments that combine minimal sample impact with high-throughput, high-precision analysis of nanoscale behavior. These tools will provide insight into how nanomaterials evolve, interact, and function—unlocking a deeper understanding of their mechanisms and informing better design across applications.

14. How can nanotechnology be used to build engineered tissues and organs for biological research and medicine? Nanomaterials offer powerful capabilities to replicate biological complexity in engineered systems.[358] By mimicking the nanoscale structure of extracellular matrices (ECMs), materials such as electrospun fibers, hydrogels, and nanoparticles can support cellular adhesion, growth, and differentiation.[359−362] These scaffolds can be engineered to deliver spatially and temporally resolved chemical and mechanical signals, enabling detailed study of biological processes and disease states.[363−369]

Advances in 3D printing using nanocomposite inks now enable fabrication of vascularized organ-like structures.[370] Integration of nanomaterials into these systems permits embedded sensing of stress, pH, or metabolite levels over time.[371−373] These capabilities are being used to explore phenomena such as metastasis in flowing environments,[374]

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

stem cell differentiation through electrical signals,[375] and protein expression in response to drugs or toxins.[376]

Organ-on-chip (OoC) models have gained attention for their ability to recreate organ-specific microenvironments.[377,378] During the COVID-19 pandemic, they accelerated drug testing. The emerging field of body-on-chip (BoC) platforms connects multiple OoCs to simulate systemic human physiology.[379,380] These platforms offer new possibilities for personalized medicine and miniaturized clinical trials.[381]

Real-time monitoring remains a key challenge. Nanobiosensors, including electrochemical, mechanical, and optical devices, can detect biomarkers such as troponin in cardiac chips, glutamate in brain models, or oxygen in tumor environments.[382−385] Cyborg organoids, living tissues integrated with stretchable nanoelectronics, enable continuous sensing of cellular activity, a significant advance in studying tissue responses.[386,387]

To scale these systems and to ensure reproducibility, interdisciplinary efforts are needed. Biologists and engineers must codesign platforms that balance biological relevance with manufacturability and analytical access. With ongoing improvements in nanomaterials and sensing technologies, engineered tissues and organs are becoming indispensable tools for biomedical discovery and therapeutic development.

MAKING SCIENTIFIC LABOR AND DECISION-MAKING PROCESSES MORE EFFICIENT

15. How can AI and ML accelerate nanomaterial discovery through inverse design? Inverse design, identifying a desired property and working backward to find a structure that achieves it, is transforming nanomaterials discovery. AI and ML play pivotal roles in this process by mapping synthesis-structure−property relationships and predicting candidate materials with desired functions.[31,388,389]

Generative ML models such as variational autoencoders and generative adversarial networks can propose new molecular structures with targeted properties.[390,391] However, to ensure trust and transparency, interpretable ML methods, like SHAP (SHapley Additive exPlanations) or physics-informed neural networks, are needed to identify key features driving performance.[392−395]

A major limitation is data. High-quality, large-scale data sets are essential for training ML models. High-throughput experimental methods, megalibraries, and first-principles simulations such as density functional theory (DFT) are generating foundational data, but broader efforts are needed to scale and standardize these processes.[156,159−161,396−400] Public databases like the Open Quantum Materials Database and Materials Project can accelerate access and collaboration.[401−403] Crucially, inverse design requires iterative, closed-loop systems where AI predictions are validated by experiments, which then provide feedback to improve the model. Such loops reduce time and resource use while enabling optimization of materials for specific applications.[404−406]

As the field matures, the combination of AI/ML with automated synthesis, advanced characterization, and open data will transform materials development—from trial-and-error discovery to hypothesis-driven innovation. In nanoscience, where the combinatorial space is immense and structure−property relationships are complex, inverse design offers a powerful path to accelerate the development of next-generation materials. Another type of iterative closed-loop approach, genetic algorithms, has been successfully applied[407] to design nanoplasmonic devices and invert experimental data into structural information. Because of the stochastic nature of this approach, it is numerically expensive. On the other hand, it has the advantages of stability and generality.

16. How can AI and robotics be combined to automate laboratory workflows in nanoscience and nanotechnology? The rapid advances in AI, ML, and deep learning over the past decade are transforming laboratory automation in nanoscience and nanotechnology. Models like convolutional neural networks (CNNs) excel at computer vision tasks, such as vehicle detection,[408,409] while recurrent neural networks (RNNs) and generative pretrained transformer (GPT) models power language understanding and generative tasks.[410,411] Such AI models, combined with robotics, enable automation of routine laboratory tasks, increasing reproducibility and freeing researchers to focus on data analysis and experimental design.[412−414]

The integration of AI and robotics promises scalable, high-throughput experimentation beyond human capacity.[397,415] For example, AI can mine the literature to identify key nanoparticle synthesis parameters. Robotic platforms can then perform, monitor, and characterize syntheses in real time. Iterative feedback using ML models can refine synthesis conditions automatically by correlating parameters to nanoparticle properties. "Self-driving labs" (SDLs) embody this concept, combining robotic automation of repetitive tasks with ML analysis of complex data sets.[397,399] Such SDLs have been used to synthesize nanoparticles, polymers, and organic molecules relevant to pharmaceuticals, catalysis, and clean energy,[416,417] although systems for synthesis under harsh conditions remain limited.[418] Carnegie Mellon University's Cloud Lab, accessible remotely, is a leading example of such SDL infrastructure.[419]

Successful AI-robotic integration depends on large, high-quality data sets for training.[420] Progress requires building data pipelines, developing interoperable software, and adopting cloud best practices across SDLs. Standardizing data formats, reproducibility protocols, and synthetic description languages would enhance integration among AI, robotics, and characterization techniques.[421,422] Moreover, automated characterization tools—especially for advanced instruments like TEM, SEM, and synchrotron X-ray spectroscopies—should be integrated into SDL workflows.[399,423] Together, these advances point toward fully autonomous laboratories that accelerate discovery and translation in nanoscience and nanotechnology.

17. How can we improve early stage prediction of nanomedicine efficacy in humans? Predicting how nanomedicines will perform in humans remains a major challenge that slows development down. Like all drugs, nanomedicines must pass rigorous preclinical testing, including *in vitro* cell culture studies and *in vivo* animal models, before clinical trials.[424] However, these models often fail to predict human outcomes reliably.[425] Cultured human cells are typically transformed immortalized lines or clonal populations that poorly represent patient heterogeneity. Primary human cells are scarce and short-lived. Animal models differ in genetic homology and immune responses, which complicates translation. Many nanomedicines, particularly immune therapies, require intact human microenvironments not replicated in standard models.

Emerging approaches aim to address these limitations. Advanced *in vitro* models, including 3D cultures and microfluidic OoC systems, more closely mimic human tissue

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

architecture and physiology.[426−432] These platforms are being explored for applications such as tumor vaccine development.[433,434] "Humanized" mouse models, engineered to express human antigens and drug targets, reduce species differences.[435−437] *Ex vivo* manipulation of human tissues from healthy or diseased donors further refines predictive assays.[438] Organoid cultures enable personalized screening, offering the possibility of tailored dosing and treatment strategies.[439−441] Such approaches could improve patient stratification and reduce trial failures by identifying effective therapies earlier.

Computational modeling and AI tools are increasingly employed to predict nanomedicine behavior, incorporating genetic, biomarker, and sex/gender differences.[442−444] Sex-based biological differences remain understudied but can significantly influence immune cell uptake of lipid nanoparticles, for example.[445] Protein corona engineering is being developed to mitigate sex-related immune variability.[446] These multidisciplinary innovations aim to accelerate nanomedicine translation, but more researchers must engage to overcome remaining challenges.

USING STANDARDIZATION TO DRIVE COLLABORATION

18. What strategies are advancing standardized, reproducible analyses in nanoscience? Nanomaterials' unique properties and the diversity of characterization techniques demand standardized approaches to ensure data reliability, reproducibility, and broad usability.[447,448] Establishing global standards for data acquisition, processing, and interpretation is essential to foster collaboration and to accelerate innovation.[449,450] Large data sets require interoperable frameworks supported by academia, industry, and standardization bodies.

Efforts focus on developing standardized protocols, automated analysis tools, and shared databases. Centralized repositories categorize nanomaterials and their properties, inspired by analogous databases in molecular biology and chemistry (*e.g.*, Protein Data Bank, Cambridge Structural Database). Initiatives include NanoCommons[451] for nanoinformatics safety data, caNanoLab[452,453] and Nanotechnology Characterization Laboratory[454] for nanomedicine safety and characterization, and NaKnowBase (NKB)[455] and Nano-Informatics Knowledge Commons (NIKC)[456] for biological and environmental data. The Materials Project[401,457,458] and Electrolyte Genome[459] gather materials data for energy applications. Nano[460] curates nanomaterial literature data. AI-powered platforms like eNanoMapper[461] automate data analysis to reduce human error and enhance reliability.[462,463]

Standardization also expedites regulatory review and commercialization by providing consistent classifications and reducing redundant testing.[464,465] For example, NIST-developed universal research-grade test materials for SARS-CoV-2 lipid nanoparticles[466] accelerated vaccine development through harmonized analytics and collaboration.[467−469] Similar efforts are expanding to extracellular vesicles and other nanomedicines, highlighting the critical role of standardized clinical efficacy data.[470,471] Continued work is needed to broaden and deepen these standardization frameworks, ultimately hastening safe nanotechnology translation.

IMPACTFUL APPLICATIONS

Impactful applications refer to technologies that benefit large numbers of people or show strong potential to do so. Like other scientific fields, nanoscience and nanotechnology are driven by curiosity and rooted in fundamental discovery. However, broad scientific impact comes from the ability to translate these discoveries into technologies that improve lives. This translation is a key measure of the value of scientific and engineering advancements. Nanoscience and nanotechnology are already influencing a wide range of applications—from medicine to energy and the environment—reflecting the interdisciplinary nature of the field. These technologies enhance quality of life by enabling better disease treatment and tracking, improving performance, providing clean water and energy solutions, and advancing how we access, analyze, and transmit information.

ENHANCING INFORMATION PROCESSING, STORAGE, AND SHARING

19. How can nanotechnology enhance computing and data storage? Nanotechnology promises to revolutionize computing and data storage by overcoming fundamental limits of silicon-based devices.[472] Innovations at the architecture, materials, and algorithmic levels aim to increase capacity, speed, and energy efficiency critical to meeting growing demands driven by AI and ML.[473]

Nanomaterials such as graphene, quantum dots (QDs), nanosheets, and lanthanide-doped nanocrystals are integral to next-generation memory technologies.[474,475] These materials enable devices like resistive random-access memory (ReRAM) and spintronic memories that are smaller, faster, and consume less power than conventional memories.[476] Quantum computing represents a transformative frontier, utilizing qubits that exploit superposition and entanglement to solve complex problems exponentially faster than classical computers.[474] Nanophotonic circuits, which use photons rather than electrons for data transfer, promise reduced latency and higher bandwidth for future data centers and communication networks.

Biomolecules such as DNA provide another exciting platform for computation and data storage.[472,477,478] DNA's stability and dense information encoding allow massive parallelism in data processing. Techniques like polymerase chain reaction (PCR)[479] enable efficient data amplification. Recent work explores peptide arrays immobilized on self-assembled monolayers for information storage readable by mass spectrometry, encoding digital data in molecular patterns.[480] These biomolecular approaches open new pathways for ultradense, energy-efficient storage and computing, complementary to traditional silicon and emerging quantum technologies.

20. How are nanomaterials enabling faster, more secure global communication? Nanomaterials are key to advancing communication technologies that demand higher speeds, larger capacities, and improved energy efficiencies.[481−483] Two-dimensional (2D) materials such as graphene and other semiconductors exhibit exceptional electrical properties compatible with silicon technologies, enabling nanoscale transistors and photonic devices for rapid signal processing.[484−486] These advances support the development of compact antennas, flexible electronics, and enhanced optical fibers critical to modern networks.[487−490]

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

Security in global communication increasingly relies on quantum communication, leveraging quantum mechanics to provide theoretically unbreakable encryption. Quantum dots, nanodiamonds, and other nanostructures serve as single-photon emitters and qubit hosts, potentially operable at room temperature, overcoming technical hurdles in quantum information science.[491,492] Integrated photonics and on-chip signal routing reduce energy losses and bolster secure data transfer.[493,494]

These technologies pave the way for reliable, ultrafast, and secure communication networks, addressing the demands of emerging networks for 5G, 6G, and even more advanced communication systems.[495] Nanomaterial-enabled hardware will underpin future communication infrastructure by enhancing bandwidth, reducing latency, and ensuring data integrity on a global scale.

ENSURING FOOD AND WATER SECURITY

21. How can nanotechnology improve sustainable agriculture and crop protection? Nanotechnology offers promising tools to enhance agricultural sustainability, crop yield, and resilience, addressing the United Nations' Sustainable Development Goal 2 of ending hunger and achieving food security.[496] Early research has demonstrated how nanomaterials can improve the delivery efficiency and specificity of pesticides, herbicides, fertilizers, and genetic materials to plants.[497−502] These nanoenabled agrochemicals reduce active ingredient use and environmental runoff while enhancing crop resistance to pests and diseases.[497,503,504]

Nanoformulated fertilizers, such as those based on incongruent dissolution, release essential nutrients more precisely, reducing greenhouse gas emissions and mitigating food insecurity exacerbated by climate change.[505−507] Nanoclays improve water retention and nutrient delivery in arid soils, while carbon and TiO_2 nanoparticles assist in soil remediation by adsorbing pollutants.[508−510] Nanotechnology also improves disease and pathogen detection accuracy in crops and helps protect plants against environmental stresses like drought and nutrient deficiency.[511]

Despite these advances, environmental impacts of nanomaterials on soil microbiota, pH, and plant growth remain underexplored and require further study.[512−514] Insights from the field of nanomedicine, especially lessons in drug delivery, should be leveraged to accelerate the development of safe, effective nanoagrochemicals that bolster agricultural capabilities and performance in diverse environments, including extraterrestrial ones, although techno-economic analyses need to be done.[515,516]

22. How can nanotechnology be used to ensure global access to clean and safe water? Global water security depends on increasing access to clean water, including in arid and contaminated regions; indeed, more than two centuries of industrialization has polluted water supplies owing to industrial processes. Porous nanomaterials such as MOFs, covalent organic frameworks (COFs), and hydrogen-bonded organic frameworks (HOFs) have emerged as powerful materials for harvesting water from humid air.[517−520] Their high surface areas and tunable pore chemistries enable selective and efficient water capture.[521] Optimizing hydrophilicity and pore geometry tailors total uptake and working capacity.[522] Integrating MOFs into solar- or heat-driven devices enables passive, energy-efficient water release, advancing decentralized water harvesting technologies.[523]

Nanomaterials also improve desalination and purification processes.[524,525] Carbon nanotube and graphene oxide membranes enhance water transport and salt rejection, while zerovalent iron nanoparticles remove heavy metals.[510,526−528] Rapid 3D printing of filtration resins, like poly(lactic acid)-TiO_2 composites, enables on-demand, decentralized water purification with tailored contaminant capture.[529−532] Moreover, nanomaterials coatings on widely available and cost-effective sponge-based sorbents can be used to clean up contaminated bodies of water.[533−535] Such reusable, multiuse sorbents are selective for the removal of oil/organics, phosphate/fertilizer and metal contaminants. Continued development and implementation of such sustainable approaches are being commercially translated (i.e., Coral Innovations). Future research must focus on scalable, cost-effective synthesis and multicontaminant removal capabilities.

Nanomaterial-based sensors enhance water quality monitoring by detecting contaminants such as heavy metals, organic pollutants, and pathogens at trace levels.[529,536−538] Portable, low-cost devices like colorimetric strips and smartphone readers are under development to improve accessibility.[539−541] Integrating nanosensors with underwater vehicles enables *in situ*, real-time monitoring.[542] These innovations will be critical to ensuring safe drinking water worldwide, supporting environmental and public health.

SAFEGUARDING THE ENVIRONMENT

23. How can nanotechnology be applied to identify, sequester, and remediate environmental toxins? Environmental toxins and pollutants pose serious threats to both human health and ecosystems. Nanotechnology offers innovative solutions by leveraging engineered nanomaterials designed to resist, to capture, and to remediate such harmful substances.[267,543−545] Nanomaterials can be tailored at the surface and structural levels to adjust properties like hydrophobicity, electrostatic charge, pore size, surface area, and active site characteristics, enabling selective microbial resistance,[546,547] targeted pollutant capture,[548] and catalytic toxin transformation.[549] For example, nanoparticles based on earth-abundant metals like aluminum (Al) and copper−iron (Cu−Fe) have proven highly effective in catalyzing the conversion of environmental toxins such as ammonia and hydrogen sulfide.[550−552] Additionally, metal-oxide and carbon nanomaterials and dendrimers are extensively employed in remediation technologies.[553]

MOFs present another powerful approach due to their customizable pores and surface chemistry that facilitate toxin adsorption and degradation.[554−557] Some MOFs incorporate catalytic sites that break down hazardous compounds, including organophosphorus toxins, into less harmful by-products.[556] Such MOFs are used in protective gear against chemical threats.[558] Emerging challenges, such as persistent organic pollutants and microplastics, necessitate next-generation nanomaterials with enhanced selectivity and efficiency.[543] Data-driven materials design and ML platforms accelerate the development of cost-effective, earth-abundant remediation materials.[559,560] Smart adaptive nanomaterials that respond dynamically to environmental stimuli are also being explored.[561]

Nanoparticle-based cross-linking within hybrid materials imparts dynamic, robust, and recyclable properties, enabling extended operational lifetimes and facile separation and reuse.[267] Integrating these nanotechnologies with renewable

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

energy systems could yield comprehensive pollution management solutions.[548] The convergence of advanced synthesis, characterization, and sustainability drives the development of increasingly effective and environmentally conscious nanomaterial-based remediation strategies.

SPURRING THE GLOBAL CLEAN ENERGY TRANSITION

24. How can nanomaterials advance clean energy generation and sustainable fuel production? Nanomaterials play transformative roles in clean energy generation and the sustainable production of fuels, offering new pathways to reduce reliance on fossil resources.[304−306,562] The global challenge of generating abundant renewable electricity has benefited greatly from nanoscience advancements in solar, wind, hydroelectric, and tidal technologies. For example, photovoltaic (PV) cells have been enhanced through nanoengineered semiconductor surfaces, improved metal−semiconductor contacts, and plasmonic antennas, which increase charge separation and optical absorption efficiency. Silicon-based PV technologies have evolved alongside halide perovskite photovoltaics, the latter achieving single-junction efficiencies over 26% through improved interfacial passivation, charge carrier lifetimes, and stability, while lowering cost and processing constraints compared to traditional materials.

Nanotechnology also advances ocean wave energy harvesting using nanolayered metals or graphene, which confine charge motion *via* ionic strength gradients. These materials can be deposited onto marine-grade substrates, enabling large-scale integration in coastal infrastructure; however, challenges remain due to corrosive ocean environments and scaling difficulties.[563−565]

In addition, nanomaterials catalyze key chemical reactions essential for sustainable fuel production. Many industrial chemical processes are major greenhouse gas sources; transitioning to reactions powered by electricity rather than combustion is crucial. Nanocatalysts enable sustainable synthesis of hydrogen (H_2), ammonia (NH_3), methanol (CH_3OH), ethylene, propylene, and aromatics, preferably from waste feedstocks.[304−306,562,566,567] Photoelectrochemical cells employing nanomaterials can directly convert solar energy to hydrogen *via* water splitting, enhancing economic viability and environmental sustainability. Plasmonic antenna-reactor nanoparticles catalyze dry methane reforming, converting CO_2 and CH_4—the two most abundant greenhouse gases—into syngas (H_2 + CO), a precursor for synthetic fuels.

Nanostructuring allows discovery of novel active sites, unique alloy compositions, and improved atom economy through increased surface area-to-volume ratios. Furthermore, understanding nanoparticle behavior under reaction conditions using advanced hardware, software, and AI/ML tools is critical to optimize catalyst performance and accelerate clean energy technologies. Continued research into nanomaterials for energy generation promises significant progress toward a sustainable global energy transition.

25. How do nanomaterials improve the efficiency of energy storage and transport systems? Efficient, compact, and reliable energy storage is essential for applications ranging from portable electronics to grid stabilization in renewable energy systems, such as solar and wind.[568] Nanomaterials significantly enhance energy storage technologies, including batteries and supercapacitors, by providing large specific surface areas and tailored nanostructures. These features increase electrode−electrolyte contact, thereby improving charge rates, storage capacity, and mitigating issues like volume expansion during charge−discharge cycles.[569−574]

Nanoporous materials, including MOFs, zeolites, molecular sieves, and porous carbons, offer vast internal surface areas and tunable pore chemistries, making them ideal for selective storage and controlled release of gases and liquids relevant to fuel storage.[575−585] For instance, MOFs, metal hydrides, carbon nanotubes, and graphene-based materials provide high-capacity, rapid hydrogen absorption and desorption kinetics, crucial for fuel cells in transportation.[586,587] Industrial-scale production of MOFs by companies such as NuMat highlights their commercial viability.[588]

Quantum effects and coupling phenomena within or between nanomaterials open new avenues for system-level improvements in energy storage and conversion.[589,590] Spin-selective processes, exciton−phonon interactions, and exciton-polariton coupling can be engineered to optimize light absorption, carrier extraction, and catalytic activity.[591,592] Nanostructured step edges catalyze bond activation efficiently,[593] and nanoscale optical cavities amplify absorption,[594,595] collectively enhancing photocatalytic and electrocatalytic architectures.[596]

By harnessing these nanoscale phenomena, future energy storage and transport technologies could achieve higher efficiencies, longer lifetimes, and improved integration with renewable energy sources, supporting sustainable energy infrastructures worldwide.

26. How can nanomaterials address the demand for rare-earth elements amid supply and environmental challenges? Rare-earth elements (REEs) such as scandium, yttrium, and lanthanum are vital for advanced technologies, including renewable energy devices, electric vehicles (EVs), and high-performance magnets due to their unique electronic, magnetic, and luminescent properties.[597] However, global REE reserves are geographically concentrated—primarily in China, with significant deposits also in Vietnam, Russia, and Brazil—leading to supply vulnerabilities and environmental concerns linked to mining.[598] These challenges drive the need for sustainable REE extraction, separation, and recycling methods.[599]

Nanomaterials offer promising solutions due to their high surface-area-to-volume ratios and tunable structures. Materials such as MOFs, carbon nanotubes, graphene, and nanoscale collectors can be engineered to bind selectively and to extract REEs from ores and electronic waste streams, improving efficiency and sustainability of recovery processes.[600−603] Nanomaterial-enhanced filtration systems can increase separation efficacy in mining and recycling operations.[604−606] Cerium-doped nanocatalysts facilitate material breakdown to improve REE recovery, while bioinspired nanotechnologies utilize mussel-inspired nanocellulose coatings and cyanobacteria for selective REE binding from aqueous media without harmful chemicals.[607] Biodegradable protein-based adsorbents and bionanoparticles are also being developed for sustainable REE extraction.[608,609]

Another strategy is to reduce reliance on REEs by developing alternative materials.[610] AI is being used to guide materials discovery and to accelerate the identification of REE-free or reduced-REE materials. Examples include Zr_2Co_{11} and Fe−Co-based nanoparticle magnets that eliminate REEs, and Pt-REE alloy nanoparticle catalysts designed for lower REE content in hydrogen fuel cells and petroleum refining.[611−613]

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

These advances promote a sustainable supply chain for REEs critical to modern technology while addressing environmental and geopolitical concerns.

IMPROVING HUMAN HEALTH AND SAVING HUMAN LIFE

27. How can nanoscience enhance the well-being and performance of healthy individuals? Nanomedicine can be used to treat disease and to improve health, performance, and preventive care for healthy individuals.[614,615] A landmark example is the mRNA COVID-19 vaccine, which utilized nanotechnology for effective delivery and immune activation. Preventive medicine, including vaccines, has dramatically reduced infectious disease burdens and certain cancers.[616−618] Structural nanomedicine improves vaccine stability and delivery, enhancing immune responses and minimizing side effects.[619−621]

Nanotechnology also enables performance enhancement in areas such as muscle regulation, sensory augmentation *via* wearable devices, aging delay, and cognitive function improvements through targeted delivery and brain-computer interfaces.[622−624] Gene-editing tools like CRISPR, supported by nanoscale delivery systems, hold potential not only for treating genetic disorders but also for safely modifying biological moieties in otherwise healthy individuals.

Additionally, exogenous wearable, injectable, and inhalable nanosensors facilitate continuous monitoring of physical and cognitive metrics.[625−629] These sensors enable real-time data collection on health, exertion, recovery, and attention, informing personalized optimization strategies in athletics, education, and daily activities. Integration into training regimens and learning environments allows fine-tuning of performance and well-being, enhancing quality of life.

Nanoscience-driven advances in preventive medicine, performance monitoring, and cognitive enhancement offer exciting prospects for improving health and human potential, moving toward a future where technology supports proactive, personalized wellness.

28. What are the key challenges in developing nanotechnology-based tools for early disease detection? Nanotechnology promises transformative advances in early, noninvasive disease detection, crucial for timely interventions and patient self-monitoring.[630,631] Effective diagnostic tools require three key components: target recognition, signal transduction, and signal readout.[632−634] Nanomaterials contribute significantly by enabling rapid, sensitive detection beyond symptom-based methods.

Target recognition involves detecting disease-specific molecular markers using highly selective biorecognition elements such as DNA aptamers, spherical nucleic acids (SNAs), and antibodies that bind targets at ultralow concentrations.[635,636] Improving the specificity and stability of these nanoscale and biological components in complex biological fluids is a critical focus for enhancing real-world diagnostic performance.

Signal transduction converts recognition events into measurable signals. Nanoparticles amplify signal strength dramatically, increasing assay sensitivity.[637,638] Therefore, it should be an ongoing research priority to optimize nanoparticle systems to enhance signal fold-change.

Finally, signal readout must provide clear, multiplexed outputs. Nanotechnology enables multiplexed detection *via* quantum dot fluorescence, gold nanoparticle optical contrast, and other modalities, allowing simultaneous monitoring of multiple biomarkers.[639−641] Increasing multiplexing capacity while minimizing sample volumes remains an important challenge.

Integration of these components into cohesive, reliable diagnostic platforms is essential for clinical adoption. AI-driven design and analysis tools can optimize recognition elements, signal processing, and readout, improving diagnostic accuracy and enabling global healthcare impact. Overcoming these challenges will facilitate the widespread deployment of nanotechnology-enabled early detection tools.

29. What nanotechnology advances are essential to enable practical point-of-care diagnostics and stable off-the-shelf nanomedicines? Current antigen-based point-of-care (POC) diagnostic tests, such as those used for COVID-19, still rely on technology developed in the 1960s, for example in pregnancy tests, limiting their sensitivity and applicability.[642] To broaden access to affordable, reliable diagnostics—especially in low-resource settings lacking laboratory infrastructure—advanced POC platforms leveraging nanotechnology are needed.[633,643] Nanomaterials can significantly improve these platforms by enhancing target specificity, amplifying detection signals, reducing power consumption, and minimizing device size, all of which increase portability and practicality.[644,645]

In parallel, developing stable, off-the-shelf nanomedicines that maintain efficacy during long-term storage and transport is crucial.[646] Scalable 3D nanoscaffold biomanufacturing methods offer cost-effective, high-throughput production of engineered cells and nanomedicines that do not require individual personalization each time, thus enabling broader distribution. Self-assembling nanomaterials such as DNA origami-based vaccines provide modular platforms that simplify targeted therapies and reduce the complexity of individualized treatments.[647] Additionally, MOFs have been shown to encapsulate sensitive biologics, creating formulations that withstand shipping and storage stresses without losing potency.[648,649]

Achieving these goals requires close collaboration among nanotechnology researchers, pharmaceutical developers, and healthcare providers. Moreover, clear regulatory guidelines for safety, efficacy, and nanopharmaceutical quality standards are critical to enable widespread adoption. These advances could democratize healthcare by delivering powerful diagnostics and therapeutics directly to diverse populations worldwide, overcoming current infrastructure and supply chain limitations.

IMPLICATIONS FOR SOCIETY

This Nano Focus has examined how nanoscience and nanotechnology have revolutionized science and engineering—from advances in synthesis to the development of new tools and methods—and how these scientific breakthroughs have translated into technological innovations. We have highlighted key questions across these areas and proposed potential solutions to advance the field. In addition to their direct impacts, nanoscience and nanotechnology have also reshaped broader societal perspectives. The development of novel materials and systems brings unique challenges in areas such as education, ethics, policy, and intellectual property, among others.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

TEACHING NANOSCIENCE AND NANOTECHNOLOGY

30. How can nanoscience and nanotechnology be integrated effectively into educational curricula and public outreach? Nanoscience and nanotechnology represent transformative scientific fields with interdisciplinary foundations, making their integration into traditional curricula complex.[650] A key question is whether nanoscience topics should be embedded in existing chemistry, physics, and biology courses, or offered as standalone electives or degree programs, possibly within dedicated nanoscience departments.[651,652] Approaches vary widely, with some institutions focusing on graduate research exposure, while others emphasize undergraduate coursework. Collaborations with industry and government laboratories to align education with workforce demands through internships and cooperative programs have also been explored.[653]

For nanotechnology's economic and societal growth, it is essential to engage learners across educational levels. The U.S. National Nanotechnology Initiative (NNI) promotes workforce expansion *via* public outreach and education, including efforts to introduce nanoscience concepts in K−12 education, which may inspire students and indirectly educate their families.[654−656] Resources include media portrayals (*e.g.*, *Black Panther*, *Ant-Man*), interactive experiences such as Disney World's "Take a Nanooze Break", and educational books.[657,658] However, K−12 curricula often face challenges in accommodating new content due to crowded schedules and limited resources.

Digital platforms are increasingly vital in expanding nanoscience education, with online modules, simulation tools, and remote laboratories providing broader accessibility.[659] Nonetheless, hands-on laboratory experiences remain critical to effective STEM learning. Targeted funding to train teachers and support immersive university-community programs can foster lasting engagement. Partnerships between universities and community or technical colleges are also promising to build a diverse nanotechnology workforce.[655,659−661] These educational strategies aim to cultivate a scientifically literate public and prepare future innovators.

UNDERSTANDING ETHICAL RESPONSIBILITIES

31. What are the key ethical challenges posed by nanoscience and nanotechnology, and who should govern their ethical standards? Nanoscience and nanotechnology raise ethical issues common to emerging technologies: balancing innovation with safety, privacy, and societal impact. However, the rapid pace of development has often outstripped the formulation of ethical guidelines and regulations.[662,663] Future applications—such as nanobots for surveillance, nanoparticle tracers for tracking, or performance-enhancing nanomedicines—introduce complex dilemmas requiring careful ethical scrutiny.[664−667]

Ethical governance should involve the communities affected by nanotechnology, including researchers, policymakers, healthcare providers, and the public, to assess risks and benefits collaboratively. Transparent communication about the potential implications of nanotechnologies is crucial to build trust and enable informed societal decisions. Policymakers must engage the public proactively to educate and to solicit input on ethical standards.

A central challenge is balancing intellectual property protections that incentivize innovation with ensuring equitable access to nanotechnologies.[668−670] This includes safeguarding privacy while promoting transparency and public benefit. Ethical frameworks must evolve dynamically alongside technological advances, guided by multidisciplinary input and international dialogue to address global impacts. Ultimately, ethical stewardship should enable responsible innovation that maximizes societal benefit while minimizing harm.

INTEGRATING NANOSCIENCE AND PUBLIC POLICY

32. What are the main public policy challenges for nanoscience, and how can global coordination enhance regulation and innovation? Nanoscience and nanotechnology have become integral to many commercial products, from quantum dot TVs (Samsung, Sony) to lipid nanoparticle drug delivery systems (Evonik) and advanced materials (DuPont, BASF).[671] Regulatory frameworks differ by region; in the U.S., the FDA regulates many nanomaterials, while Europe applies REACH regulations with member states overseeing compliance.[672−674] These frameworks ensure safety but can fragment risk assessment and market access, complicating global exchange.

Global coordination is essential to harmonize regulations, reduce trade barriers, and create consistent safety standards. International bodies such as the International Organization for Standardization (ISO), the Organisation for Economic Cooperation and Development (OECD), and the World Health Organization (WHO) play key roles in developing and updating global regulations and testing protocols for nanomaterials.[675−681] Policies must be adaptive as new materials with novel properties emerge, addressing classification, handling, disposal, and recycling challenges.

A responsible policy approach also requires assessing long-term environmental and health impacts. For example, while heavy metal nanoparticles like those containing lead or mercury pose toxicity risks, they remain critical for applications like catalysis and imaging.[674,682,683] Balancing these risks with benefits is a continuous regulatory challenge. Ultimately, coordinated global policies can foster innovation while protecting public and environmental health, enabling nanotechnology's sustainable integration into economies worldwide.

INTEGRATING NANOSCIENCE AND NANOTECHNOLOGY WITH INTELLECTUAL PROPERTY

33. How can intellectual property (IP) frameworks support nanomaterial innovation while ensuring broad societal benefit? Balancing open innovation with protecting proprietary discoveries is vital for advancing nanoscience and translating research into public benefit. Nanoscience generates vast data sets describing material properties and interactions across various environments, often produced *via* high-throughput experiments and theoretical models.[684] Both AI and ML accelerate discovery by analyzing trends and optimizing materials for specific uses.[685−687] However, sharing data widely while protecting IP poses a significant challenge.

Adoption of FAIR principles (Findable, Accessible, Interoperable, Reusable) for data management promotes accessibility and reuse of nanomaterial data sets.[688] Emerging IP frameworks may require clear documentation of human input in AI-assisted inventions to ensure patentability without stifling collaboration. A hybrid model may evolve where foundational data remains open, while specific, application-driven innovations receive patent protection.

Bridging fundamental research and commercial application needs new funding structures and policies encouraging precompetitive collaboration. Public-private partnerships can facilitate data sharing while preserving rights necessary for market entry. Supporting environments that foster open science alongside attractive IP protections will accelerate innovation and maximize societal impact. In sum, thoughtful IP management is key to unlocking nanotechnology's full potential, balancing innovation incentives with broad access and societal benefit.

SUMMARY AND OUTLOOK

Although the questions have been grouped by themes—foundational understanding, tools and techniques, impactful applications, and societal implications—the responses reveal the deep interdependence and interdisciplinarity of these areas. Several key themes have emerged. Nanoscience and nanotechnology will advance significantly as we move closer to 1) Achieving atomically precise nanoparticles and nanostructures and gaining the ability to analyze, understand, and control their composition over time—similar to how we write and manipulate chemical reactions for molecules; 2) Developing *in situ* and *operando* characterization tools for single particles and structures, shifting from ensemble-averaged data to atomistic insights, as is possible in many molecular systems; 3) Using the nanoscale as a true bridge between the quantum and macro scales—understanding transitions across scales, controlling properties within a single system, and producing materials at scales relevant to real-world applications; 4) Leveraging AI and ML to accelerate all aspects of the field, from discovery and synthesis to application; and 5) Enhancing public understanding, societal integration, and global collaboration—recognizing that if chemistry is the "central science," then nanoscience and nanotechnology may well be the "central" central science. In summary, by posing and addressing 33 key questions in nanoscience and nanotechnology, we have established a framework to inspire and to guide future research across the field.

AUTHOR INFORMATION

Corresponding Author

Chad A. Mirkin – *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States; Chan Zuckerberg Biohub Chicago, Chicago, Illinois 60642, United States;* orcid.org/0000-0002-6634-7627; Email: chadnano@northwestern.edu

Authors

Sarah Hurst Petrosko – *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-7319-3232

Natalie Artzi – *Wyss Institute for Biologically Inspired Engineering, Harvard University, Boston, Massachusetts 02215, United States; Brigham and Woman's Hospital, Department of Medicine, Division of Engineering in Medicine, Harvard Medical School, Boston, Massachusetts 02115, United States; Institute for Medical Engineering and Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02138, United States;* orcid.org/0000-0002-2211-6069

Koray Aydin – *Department of Electrical and Computer Engineering and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-3268-2216

Austin Biaggne – *International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*

C. Jeffrey Brinker – *Departments of Chemical and Biological Engineering, Molecular Genetics and Microbiology, and the Comprehensive Cancer Center, University of New Mexico, Albuquerque, New Mexico 87131, United States;* orcid.org/0000-0002-7145-9324

Katherine E. Bujold – *Department of Chemistry and Chemical Biology, McMaster University, Hamilton, Ontario L8S 4M1, Canada;* orcid.org/0000-0002-7292-6617

Y. Charles Cao – *Department of Chemistry, University of Florida, Gainesville, Florida 32611, United States;* orcid.org/0000-0001-5476-221X

Rachel R. Chan – *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-7034-9513

Chaojian Chen – *School of Materials Science and Intelligent Engineering, Nanjing University, Suzhou 215163, China*

Peng-Cheng Chen – *Department of Materials Science and International Institute for Intelligent Nanorobots and Nanosystems, Fudan University, Shanghai 200438, China;* orcid.org/0000-0002-0411-9549

Xiaodong Chen – *Innovative Center for Flexible Devices (iFLEX), Max Planck-NTU Joint Laboratory for Artificial Senses, School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore;* orcid.org/0000-0002-3312-1664

Olivier J. G. L. Chevalier – *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*

Chung Hang Jonathan Choi – *Department of Biomedical Engineering, The Chinese University of Hong Kong, Shatin, New Territories 999077, Hong Kong SAR;* orcid.org/0000-0003-2935-7217

Richard M. Crooks – *Department of Chemistry and Biochemistry, The University of Texas at Austin, Austin, Texas 78712, United States*

Vinayak P. Dravid – *Department of Materials Science and Engineering and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-6007-3063

Jingshan S. Du – *Physical Sciences Division, Pacific Northwest National Laboratory, Richland, Washington 99354, United States;* orcid.org/0000-0002-4932-6699

Sasha B. Ebrahimi – *Drug Product Development, Emerging Drug Delivery Platforms, GSK, Collegeville, Pennsylvania 19426, United States;* orcid.org/0000-0003-2752-5109

Hongyou Fan – *Sandia National Laboratories, Albuquerque, New Mexico 87185, United States; Department of Chemical and Biological Engineering, University of New Mexico, Albuquerque, New Mexico 87131, United States*

Omar K. Farha – *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-9904-9845

C. Adrian Figg – *Department of Chemistry and Macromolecules Innovation Institute, Virginia Tech,*

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933–31968

Blacksburg, Virginia 24061, United States; orcid.org/0000-0003-3514-7750
Tanner D. Fink − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0003-2102-3220
Connor M. Forsyth − *Interdisciplinary Biological Sciences Graduate Program and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*
Harald Fuchs − *University of Münster, Physikalisches Institut and Center for Nanotechnology, Münster 48149, Germany;* orcid.org/0000-0003-3394-3147
Franz M. Geiger − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-8569-4045
Nathan C. Gianneschi − *Departments of Chemistry, Materials Science and Engineering, Biomedical Engineering, and Pharmacology, and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-9945-5475
Kyle J. Gibson − *Department of Chemistry, Alma College, Alma, Michigan 48801, United States*
David S. Ginger − *Department of Chemistry, University of Washington, Seattle, Washington 98195, United States;* orcid.org/0000-0002-9759-5447
SiShi Guo − *MOE International Joint Research Laboratory on Synthetic Biology and Medicines, School of Biology and Biological Engineering, South China University of Technology, Guangzhou 510006, China*
Justin S. Hanes − *Department of Ophthalmology and Center for Nanomedicine at Wilmer Eye Institute, School of Medicine, Johns Hopkins University, Baltimore, Maryland 21231, United States; Department of Chemical and Biomolecular Engineering, Whiting School of Engineering, Johns Hopkins University, Baltimore, Maryland 21218, United States*
Liangliang Hao − *Department of Biomedical Engineering, Boston University, Boston, Massachusetts 02215, United States*
Jin Huang − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-2882-2634
Bryan M. Hunter − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-8559-9304
Fengwei Huo − *Nanjing Tech University, Nanjing, Jiangsu 210037, China;* orcid.org/0000-0002-5318-4267
Jeongmin Hwang − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-8799-3209
Rongchao Jin − *Department of Chemistry, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States;* orcid.org/0000-0002-2525-8345
Shana O. Kelley − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States; Chan Zuckerberg Biohub Chicago, Chicago, Illinois 60642, United States;* orcid.org/0000-0003-3360-5359
Thomas J. Kempa − *Department of Chemistry, Johns Hopkins University, Baltimore, Maryland 21218, United States;* orcid.org/0000-0002-1672-8325
Youngeun Kim − *Department of Materials Science and Engineering and Research Institute of Advanced Materials (RIAM), Seoul National University, Seoul 08826, South Korea;* orcid.org/0000-0002-9404-6936
Sergej Kudruk − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*
Sneha Kumari − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-5245-7016
Kaitlin M. Landy − *Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, United States*
Ki-Bum Lee − *Department of Chemistry and Chemical Biology, Rutgers University, Piscataway, New Jersey 08854, United States*
Noel J. Leon − *International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-8865-1566
Jun Li − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*
Yuanwei Li − *Department of Materials Science and Engineering, Stanford University, Stanford, California 94305, United States*
Zhiwei Li − *Department of Chemistry and Biochemistry, University of Maryland, Maryland 20742, United States;* orcid.org/0000-0002-1489-4506
Bin Liu − *Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore 119077, Singapore;* orcid.org/0000-0002-0956-2777
Guoliang Liu − *Department of Chemistry, Virginia Tech, Blacksburg, Virginia 24061, United States;* orcid.org/0000-0002-6778-0625
Xiaogang Liu − *Department of Chemistry, National University of Singapore, Singapore 117543, Singapore*
Luis M. Liz-Marzán − *CIC biomaGUNE, Basque Research and Technology Alliance (BRTA), Donostia-San Sebastián 20014, Spain; Ikerbasque, Bilbao 48009, Spain; University of Vigo, 36310 Vigo, Spain;* orcid.org/0000-0002-6647-1353
Jochen H. Lorch − *Northwestern University, Feinberg School of Medicine, Department of Hematology and Oncology, Chicago, Illinois 60611, United States; International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*
Taokun Luo − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-5894-0490
Robert J. Macfarlane − *Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States;* orcid.org/0000-0001-9449-2680
Jill E. Millstone − *Departments of Chemistry, Chemical Engineering, and Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, United States;* orcid.org/0000-0002-9499-5744
Milan Mrksich − *Departments of Chemistry, Biomedical Engineering, and Cell and Developmental Biology and*

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

International Institute for Nanotechnology Northwestern University, Evanston, Illinois 60208, United States; orcid.org/0000-0002-4964-796X

Catherine J. Murphy − *Department of Chemistry, University of Illinois Urbana−Champaign, Urbana, Illinois 61801, United States; Chan Zuckerberg Biohub Chicago, Chicago, Illinois 60642, United States;* orcid.org/0000-0001-7066-5575

Rajesh R. Naik − *MINED XAI, Dayton, Ohio 45402, United States*

Andre E. Nel − *David Geffen School of Medicine and California NanoSystems Institute, University of California, Los Angeles, California 90095, United States;* orcid.org/0000-0002-5232-4686

Christopher Oetheimer − *Department of Chemistry and Chemical Biology, Northeastern University, Boston, Massachusetts 02115, United States*

Jenny K. Hedlund Orbeck − *International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*

So-Jung Park − *Department of Chemistry and Nanoscience, Ewha Womans University, Seoul 03760, Korea;* orcid.org/0000-0002-6364-3754

Benjamin E. Partridge − *Department of Chemistry, University of Rochester, Rochester, New York 14627, United States;* orcid.org/0000-0003-2359-1280

Nicholas A. Peppas − *McKetta Department of Chemical Engineering, Department of Biomedical Engineering, Institute for Biomaterials, Drug Delivery and Regenerative Medicine, Department of Pediatrics and Department of Surgery and Perioperative Care, Dell Medical School, The University of Texas at Austin, Austin, Texas 78712, United States;* orcid.org/0000-0003-0894-5626

Michelle L. Personick − *Department of Chemistry, University of Virginia, Charlottesville, Virginia 22904, United States;* orcid.org/0000-0003-4747-9429

Arindam Raj − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-7277-6770

Namrata Ramani − *Wyss Institute for Biologically Inspired Engineering, Harvard University, Boston, Massachusetts 02215, United States; Brigham and Woman's Hospital, Department of Medicine, Division of Engineering in Medicine, Harvard Medical School, Boston, Massachusetts 02115, United States; Institute for Medical Engineering and Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02138, United States;* orcid.org/0000-0001-8159-2842

Michael B. Ross − *Department of Chemistry, University of Massachusetts Lowell, Lowell, Massachusetts 01854, United States;* orcid.org/0000-0002-2511-0594

Stacey Barnaby Ross − *Quanterix, Billerica, Massachusetts 01821, United States*

Edward H. Sargent − *Departments of Chemistry and Electrical and Computer Engineering and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0003-0396-6495

Tanushri Sengupta − *International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0009-0009-4902-4007

George C. Schatz − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0001-5837-4740

Dwight S. Seferos − *Department of Chemistry, University of Toronto, Toronto, Ontario M5S 3H6, Canada; Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario M5S 3E5, Canada;* orcid.org/0000-0001-8742-8058

Tamar Seideman − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-0643-3742

Soyoung Eileen Seo − *School for Engineering of Matter, Transport and Energy, Biodesign Center for Sustainable Macromolecular Materials and Manufacturing, Arizona State University, Tempe, Arizona 85287, United States;* orcid.org/0000-0003-1593-4474

Bo Shen − *Department of Materials Science and Engineering, City University of Hong Kong, Kowloon, Hong Kong 999077, China;* orcid.org/0000-0001-8011-7134

Wooyoung Shim − *Department of Materials Science and Engineering, Center for Multi-Dimensional Materials, Center for Nanomedicine, Institute for Basic Science (IBS), and Yonsei IBS Institute, Yonsei University, Seoul 03722, Korea;* orcid.org/0000-0002-7601-6282

Donghoon Shin − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-5017-547X

Ulrich Simon − *Institute of Inorganic Chemistry, RWTH Aachen University, 52074 Aachen, Germany;* orcid.org/0000-0002-6118-0573

Andrew J. Sinegra − *Department of Analytical Research and Development, Merck & Co., Inc., West Point, Pennsylvania 19486, United States*

Peter T. Smith − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-8892-3752

Alexander M. Spokoyny − *Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, California 90095, United States; California NanoSystems Institute, University of California, Los Angeles, Los Angeles, California 90095, United States;* orcid.org/0000-0002-5683-6240

Peter J. Stang − *Department of Chemistry, University of Utah, Salt Lake City, Utah 84112, United States;* orcid.org/0000-0002-2307-0576

Alexander H. Stegh − *Department of Neurosurgery, The Brain Tumor Center, Washington University School of Medicine, Alvin J. Siteman Comprehensive Cancer Center, St. Louis, Missouri 63110, United States*

†**J. Fraser Stoddart** − *Department of Chemistry, The University of Hong Kong, Hong Kong 999077, P. R. China;* orcid.org/0000-0003-3161-3697

Dayne F. Swearer − *Department of Chemistry, Department of Chemical and Biological Engineering, and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*

Weihong Tan − *Department of Pathology, Zhejiang Cancer Hospital, The Key Laboratory of Zhejiang Province for Aptamers and Theranostics, Hangzhou Institute of Medicine*

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

(HIM), Chinese Academy of Sciences, Hangzhou, Zhejiang 310022, China; Molecular Science and Biomedicine Laboratory (MBL), State Key Laboratory of Chemo/Biosensing and Chemometrics, College of Chemistry and Chemical Engineering, College of Biology, Aptamer Engineering Center of Hunan Province, Hunan University, Changsha, Hunan 410082, China

Michelle H. Teplensky − *Department of Biomedical Engineering and Division of Materials Science and Engineering, Boston University, Boston, Massachusetts 02215, United States;* orcid.org/0000-0003-4664-420X

C. Shad Thaxton − *Northwestern University, Feinberg School of Medicine, Department of Urology, Chicago, Illinois 60611, United States; International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States*

David R. Walt − *Wyss Institute for Biologically Inspired Engineering, Harvard University, Boston, Massachusetts 02215, United States; Department of Pathology, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts 02115, United States;* orcid.org/0000-0002-5524-7348

Mary X. Wang − *Convergence Research, West Chester Township, Ohio 45069, United States*

Zhe Wang − *Department of Chemical and Biochemical Engineering, University of Iowa, Iowa City, Iowa 52242, United States*

Wei David Wei − *Department of Chemistry and Center for Catalysis, University of Florida, Gainesville, Florida 32611, United States;* orcid.org/0000-0002-3121-5798

Paul S. Weiss − *Departments of Chemistry and Biochemistry, Bioengineering, and Materials Science and Engineering, University of California, California 90095, United States; California NanoSystems Institute, University of California, Los Angeles, Los Angeles, California 90095, United States;* orcid.org/0000-0001-5527-6248

Peter H. Winegar − *California Institute for Quantitative Biosciences (QB3 Institute), University of California at Berkeley, Berkeley, California 94720, United States; Biological Systems and Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States; Joint BioEnergy Institute, Lawrence Berkeley National Laboratory, Emeryville, California 94608, United States;* orcid.org/0000-0003-0984-4990

Younan Xia − *The Wallace H. Coulter Department of Biomedical Engineering and School of Chemistry and Biochemistry, Georgia Institute of Technology and Emory University, Atlanta, Georgia 30332, United States;* orcid.org/0000-0003-2431-7048

Yi Xie − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-7647-9666

Xiaoyang Xu − *Department of Chemical and Materials Engineering and Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, New Jersey 07102, United States;* orcid.org/0000-0002-1634-3329

Peidong Yang − *Departments of Chemistry and Materials Science and Engineering, University of California Berkeley, Berkeley, California 94720, United States;* orcid.org/0000-0003-4799-1684

Yiming Yang − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0009-0008-5010-2749

Zihao Ye − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0003-0616-5650

Kuk Ro Yoon − *Department of Chemistry, Hannam University, Daejeon 34430, South Korea*

Cuizheng Zhang − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0003-3342-7003

Hua Zhang − *Department of Chemistry, City University of Hong Kong, Kowloon, Hong Kong 999077, China;* orcid.org/0000-0001-9518-740X

Ke Zhang − *Department of Chemistry and Chemical Biology, Northeastern University, Boston, Massachusetts 02115, United States*

Liangfang Zhang − *Aiiso Yufeng Li Family Department of Chemical and Nano Engineering, University of California San Diego, La Jolla, California 92093, United States;* orcid.org/0000-0003-0637-0654

Xiaoyu Zhang − *Department of Chemistry and International Institute for Nanotechnology, Northwestern University, Evanston, Illinois 60208, United States;* orcid.org/0000-0002-0951-9664

Ye Zhang − *Frontiers Science Center for Transformative Molecules, Shanghai Jiao Tong University, Shanghai 200240, China*

Zijian Zheng − *The Hong Kong Polytechnic University, Hong Kong 999077, China*

Wenjie Zhou − *Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States*

Shengshuang Zhu − *Arbor Biotechnologies, Cambridge, Massachusetts 02140, United States*

Wei Zhu − *MOE International Joint Research Laboratory on Synthetic Biology and Medicines, School of Biology and Biological Engineering, South China University of Technology, Guangzhou 510006, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsnano.5c12854

Notes

The authors declare the following competing financial interest(s): A.H.S. is a shareholder of Exicure Inc., which develops SNA therapeutic platforms. A.H.S. is an inventor on patent US20150031745A1, which describes SNA nanoconjugates that cross the blood-brain barrier. V.P.D. is co-founder of Coral Innovations, a nanotech start-up that is commercializing IP on water cleanup from NU. C.A.M. has financial interests in Azul 3D, Inc., TERA-print, LLC, Mattiq, Inc., and Flashpoint, Inc., which could potentially benefit from the outcomes of this research.

†J. Fraser Stoddart: Deceased.

ACKNOWLEDGMENTS

Support is acknowledged from the NSF (CHE-2304909, CHE-2347622, CHE-1808539, CHE-2004238, CHE-2153191, CHE-2404203, 2418613, 2108612, 2001606, DMR-1352328, DMR-2019444, DMR-2411680, DMR-2004899, DMR 2403955, DMR-2428112, ECCS-2025633), DOE (DE-

SC0004752, DE-SC0023342, DE-SC0025488, DE-SC0025283), NIH (R00CA237861, F32GM153046, R01CA275430, R01EB022025, 1R01NS130836-01A1, RM1NS133003-01, R21NS132556-01, R35GM157326, 2R01HL139001, R01CA257926, U54DK137516), Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, ID: 390919832), European Research Council (Synergy Grant #101166855), New Jersey Commission on Spinal Cord Research (CSCR22ERG023, CSCR24IRG005), Alzheimer's Association (AARG-NTF-21-847862), Congressionally Directed Medical Research Programs (OCRP, OC220235P1), AFOSR (FA9550-23-1-0210, FA-9550-22-1-0300), ARO (W911NF-23-2-0101, W911NF-23-1-0285, W911NF-25-2-0018), US Army (W911QY25P0006), Air Force (agreement FA8650-21-2-5028 through the support of Bioindustrial Manufacturing and Design Ecosystem (BioMADE), Toyota Research Institute, Inc., Edgar H. Bachrach through the Bachrach Family Foundation, Lefkofsky Family Foundation, Arnold and Mabel Beckman Foundation, The Hartwell Foundation, W. M. Keck Foundation, Challenge Initiative (UCLA), National Natural Science Foundation of China (Award number 62288102), Gustavus and Louise Pfeiffer Research Foundation, National Research Foundation of Korea (RS-2024-00397807, RS-2023-00274736), Natural Sciences and Engineering Research Council of Canada (NSERC), University of Toronto's Acceleration Consortium from the Canada First Research Excellence Fund (CFREF-2022-00042), UT Institute for Biomaterials, Drug Delivery, and Regenerative Medicine, UT-Portugal Collaborative Research Program, Washington Research Foundation, 2025 Daejeon RISE Project (funded by the Ministry of Education and Daejeon Metropolitan City in the Republic of Korea), and Stanford Science Fellowship. Start-up funds from the University of Iowa, the University of Maryland College Park, Seoul National University, and Boston University are acknowledged. C.A.M. and C.J.M. are CZ Biohub Investigators. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. PNNL is a multiprogram national laboratory operated for the DOE by Battelle under Contract DE-AC05-76RL01830. This manuscript is the result of funding in whole or in part by the National Institutes of Health (NIH). It is subject to the NIH Public Access Policy. Through acceptance of this federal funding, NIH has been given a right to make this manuscript publicly available in PubMed Central upon the Official Date of Publication, as defined by NIH. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funding agencies or the United States Government. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

REFERENCES

(1) Binnig, G.; Rohrer, H. Scanning Tunneling Microscopy—From Birth to Adolescence (Nobel Lecture). *Angew. Chem. Int. Ed.* **1987**, *26*, 606−614.

(2) Smalley, R. E. Discovering the Fullerenes (Nobel Lecture). *Angew. Chem. Int. Ed.* **1997**, *36*, 1594−1601.

(3) *Three Paths to a Nobel Prize in Chemistry*. https://www.cas.org/resources/cas-insights/three-paths-to-a-nobel-prize-in-chemistry (accessed 2025 January 30).

(4) Eigler, D. M.; Schweizer, E. K. Positioning Single atoms with a Scanning Tunneling Microscope. *Nature* **1990**, *344*, 524−526.

(5) Weiss, P. S.; Eigler, D. M. Adsorption and Accommodation of Xe on Pt{111}. *Phys. Rev. Lett.* **1992**, *69*, 2240−2243.

(6) Crommie, M. F.; Lutz, C. P.; Eigler, D. M. Confinement of Electrons to Quantum Corrals on a Metal Surface. *Science* **1993**, *262*, 218−220.

(7) Jin, R.; Zeng, C.; Zhou, M.; Chen, Y. Atomically Precise Colloidal Metal Nanoclusters and Nanoparticles: Fundamentals and Opportunities. *Chem. Rev.* **2016**, *116*, 10346−10413.

(8) Higaki, T.; Zhou, M.; Lambright, K. J.; Kirschbaum, K.; Sfeir, M. Y.; Jin, R. Sharp Transition from Nonmetallic Au_{246} to Metallic Au_{279} with Nascent Surface Plasmon Resonance. *J. Am. Chem. Soc.* **2018**, *140*, 5691−5695.

(9) Bose, P.; Kumaranchira Ramankutty, K.; Chakraborty, P.; Khatun, E.; Pradeep, T. A Concise Guide to Chemical Reactions of Atomically Precise Noble Metal Nanoclusters. *Nanoscale* **2024**, *16*, 1446−1470.

(10) Trindell, J. A.; Duan, Z.; Henkelman, G.; Crooks, R. M. Well-Defined Nanoparticle Electrocatalysts for the Refinement of Theory. *Chem. Rev.* **2020**, *120*, 814−850.

(11) Millstone, J. E.; Wei, W.; Jones, M. R.; Yoo, H.; Mirkin, C. A. Iodide Ions Control Seed-Mediated Growth of Anisotropic Gold Nanoparticles. *Nano Lett.* **2008**, *8*, 2526−2529.

(12) Langille, M. R.; Personick, M. L.; Zhang, J.; Mirkin, C. A. Defining Rules for the Shape Evolution of Gold Nanoparticles. *J. Am. Chem. Soc.* **2012**, *134*, 14542−14554.

(13) Personick, M. L.; Mirkin, C. A. Making Sense of the Mayhem behind Shape Control in the Synthesis of Gold Nanoparticles. *J. Am. Chem. Soc.* **2013**, *135*, 18238−18247.

(14) Du, J. S.; Zhou, W.; Rupich, S. M.; Mirkin, C. A. Twin Pathways: Discerning the Origins of Multiply Twinned Colloidal Nanoparticles. *Angew. Chem. Int. Ed.* **2021**, *60*, 6858−6863.

(15) Shi, Y.; Lyu, Z.; Zhao, M.; Chen, R.; Nguyen, Q. N.; Xia, Y. Noble-Metal Nanocrystals with Controlled Shapes for Catalytic and Electrocatalytic Applications. *Chem. Rev.* **2021**, *121*, 649−735.

(16) McDarby, S. P.; Personick, M. L. Potential-Controlled (R)Evolution: Electrochemical Synthesis of Nanoparticles with Well-Defined Shapes. *ChemNanoMat* **2022**, *8*, e202100472.

(17) Weiner, R. G.; Kunz, M. R.; Skrabalak, S. E. Seeding a New Kind of Garden: Synthesis of Architecturally Defined Multimetallic Nanostructures by Seed-Mediated Co-Reduction. *Acc. Chem. Res.* **2015**, *48*, 2688−2695.

(18) Yang, T.-H.; Ahn, J.; Shi, S.; Wang, P.; Gao, R.; Qin, D. Noble-Metal Nanoframes and their Catalytic Applications. *Chem. Rev.* **2021**, *121*, 796−833.

(19) Liu, L.; Corma, A. Bimetallic Sites for Catalysis: From Binuclear Metal Sites to Bimetallic Nanoclusters and Nanoparticles. *Chem. Rev.* **2023**, *123*, 4855−4933.

(20) Zeng, C.; Chen, Y.; Kirschbaum, K.; Lambright, K. J.; Jin, R. Emergence of Hierarchical Structural Complexities in Nanoparticles and Their Assembly. *Science* **2016**, *354*, 1580−1584.

(21) Li, Y.; Zhou, W.; Tanriover, I.; Hadibrata, W.; Partridge, B. E.; Lin, H.; Hu, X.; Lee, B.; Liu, J.; Dravid, V. P.; Aydin, K.; Mirkin, C. A. Open-Channel Metal Particle Superlattices. *Nature* **2022**, *611*, 695−701.

(22) Zhou, W.; Li, Y.; Partridge, B. E.; Mirkin, C. A. Engineering Anisotropy into Organized Nanoscale Matter. *Chem. Rev.* **2024**, *124*, 11063−11107.

(23) Zhou, W.; Li, Y.; Je, K.; Vo, T.; Lin, H.; Partridge, B. E.; Huang, Z.; Glotzer, S. C.; Mirkin, C. A. Space-Tiled Colloidal Crystals from DNA-Forced Shape-Complementary Polyhedra Pairing. *Science* **2024**, *383*, 312−319.

(24) Crooks, R. M.; Zhao, M.; Sun, L.; Chechik, V.; Yeung, L. K. Dendrimer-Encapsulated Metal Nanoparticles: Synthesis, Character-

ization, and Applications to Catalysis. *Acc. Chem. Res.* **2001**, *34*, 181−190.
(25) Roldan Cuenya, B.; Behafarid, F. Nanocatalysis: Size- and Shape-Dependent Chemisorption and Catalytic Reactivity. *Surf. Sci. Rep.* **2015**, *70*, 135−187.
(26) Liu, L.; Corma, A. Metal Catalysts for Heterogeneous Catalysis: From Single Atoms to Nanoclusters and Nanoparticles. *Chem. Rev.* **2018**, *118*, 4981−5079.
(27) Chen, Y.; Lai, Z.; Zhang, X.; Fan, Z.; He, Q.; Tan, C.; Zhang, H. Phase Engineering of Nanomaterials. *Nat. Rev. Chem.* **2020**, *4*, 243−256.
(28) Kelm, J. E.; Dempsey, J. L. Metal-Dictated Reactivity of Z-Type Ligands to Passivate Surface Defects on CdSe Nanocrystals. *J. Am. Chem. Soc.* **2024**, *146*, 5252−5262.
(29) Huang, K.; Shin, K.; Henkelman, G.; Crooks, R. M. Correlating Surface Structures and Electrochemical Activity Using Shape-Controlled Single-Pt Nanoparticles. *ACS Nano* **2021**, *15*, 17926−17937.
(30) Wahl, C. B.; Aykol, M.; Swisher, J. H.; Montoya, J. H.; Suram, S. K.; Mirkin, C. A. Machine Learning-Accelerated Design and Synthesis of Polyelemental Heterostructures. *Sci. Adv.* **2021**, *7*, eabj5505.
(31) Ye, Z.; Shen, B.; Kang, D.; Shen, J.; Huang, J.; Wang, Z.; Huang, L.; Wolverton, C. M.; Mirkin, C. A. A Data-Driven Approach for the Guided Regulation of Exposed Facets in Nanoparticles. *Nat. Synth* **2024**, *3*, 922−929.
(32) Xiong, X. L.; Ma, H. X.; Tao, X.; Li, J. X.; Su, Y. J.; Zhou, Q. J.; Volinsky, A. A. Hydrostatic Pressure Effects on the Kinetic Parameters of Hydrogen Evolution and Permeation in Armco Iron. *Electrochim. Acta* **2017**, *255*, 230−238.
(33) Jarju, J. J.; Figueiredo, M. C.; Kolen'ko, Y. V. Chapter 8 - Electrocatalysis using Nanomaterials. In *Frontiers of Nanoscience*, Wain, A. J.; Dickinson, E. J. F., Eds.; Vol. *18*; Elsevier, 2021; pp 343−420.
(34) Kim, J.; Choi, H.; Kim, D.; Park, J. Y. Operando Surface Studies on Metal-Oxide Interfaces of Bimetal and Mixed Catalysts. *ACS Catal.* **2021**, *11*, 8645−8677.
(35) Koo, K.; Shen, B.; Baik, S.-I.; Mao, Z.; Smeets, P. J. M.; Cheuk, I.; He, K.; dos Reis, R.; Huang, L.; Ye, Z.; Hu, X.; Mirkin, C. A.; Dravid, V. P. Formation Mechanism of High-Index Faceted Pt-Bi Alloy Nanoparticles by Evaporation-Induced Growth from Metal Salts. *Nature Commun.* **2023**, *14*, 3790.
(36) Zhou, Y.; Li, M.; Zhang, T.; Chen, Y.; Li, X.; Jia, H.; Xu, P.; Li, X. Cooperative Characterization of *In Situ* TEM and Cantilever-TGA to Optimize Calcination Conditions of MnO_2 Nanowire Precursors. *Nano Lett.* **2023**, *23*, 2412−2420.
(37) Stapelfeldt, H.; Seideman, T. Colloquium: Aligning Molecules with Strong Laser Pulses. *Rev. Mod. Phys.* **2003**, *75*, 543−557.
(38) Gygi, F.; Galli, G. *ab initio* Simulation in Extreme Conditions. *Mater. Today* **2005**, *8*, 26−32.
(39) Richard, P.; Castellano, A.; Béjaud, R.; Baguet, L.; Bouchet, J.; Geneste, G.; Bottin, F. *ab Initio* Phase Diagram of Gold in Extreme Conditions. *Phys. Rev. Lett.* **2023**, *131*, 206101.
(40) Ye, Z.; Shen, B.; Kang, D.; Huang, J.; Wang, Z.; Wahl, C. B.; Shin, D.; Huang, L.; Shen, J.; Wolverton, C. M.; Mirkin, C. A. Using Surface Composition and Energy to Control the Formation of Either Tetrahexahedral or Hexoctahedral High-Index Facet Nanostructures. *J. Am. Chem. Soc.* **2024**, *146*, 13519−13526.
(41) Rostislav Andrievski, A. K. *Nanomaterials in Extreme Environments*; Springer: Cham, 2016. DOI: 10.1007/978-3-319-25331-2.
(42) Eswarappa Prameela, S.; Pollock, T. M.; Raabe, D.; Meyers, M. A.; Aitkaliyeva, A.; Chintersingh, K.-L.; Cordero, Z. C.; Graham-Brady, L. Materials for Extreme Environments. *Nat. Rev. Mater.* **2023**, *8*, 81−88.
(43) Yao, Y.; Dong, Q.; Brozena, A.; Luo, J.; Miao, J.; Chi, M.; Wang, C.; Kevrekidis, I. G.; Ren, Z. J.; Greeley, J.; Wang, G.; Anapolsky, A.; Hu, L. High-Entropy Nanoparticles: Synthesis-Structure-Property Relationships and Data-Driven Discovery. *Science* **2022**, *376*, eabn3103.
(44) Hsu, W.-L.; Tsai, C.-W.; Yeh, A.-C.; Yeh, J.-W. Clarifying the Four Core Effects of High-Entropy Materials. *Nat. Rev. Chem.* **2024**, *8*, 471−485.
(45) Barsoum, M. *Fundamentals of Ceramics*, 2nd ed.; CRC Press, 2019. DOI: 10.1201/9781498708166.
(46) Wyatt, B. C.; Nemani, S. K.; Hilmas, G. E.; Opila, E. J.; Anasori, B. Ultra-High Temperature Ceramics for Extreme Environments. *Nat. Rev. Mater.* **2024**, *9*, 773−789.
(47) Zhang, L.; Tang, Y.; Khan, A. R.; Hasan, M. M.; Wang, P.; Yan, H.; Yildirim, T.; Torres, J. F.; Neupane, G. P.; Zhang, Y.; Li, Q.; Lu, Y. 2D Materials and Heterostructures at Extreme Pressure. *Adv. Sci.* **2020**, *7*, 2002697.
(48) Mirkin, C. A.; Mrksich, M.; Artzi, N. The Emerging Era of Structural Nanomedicine. *Nat. Rev. Bioeng.* **2025**, *3*, 526.
(49) Mirkin, C. A.; Langer, R.; Mrksich, M.; Margolin, A. A.; Petrosko, S. H.; Artzi, N. Blueprints for Better Drugs: The Structural Revolution in Nanomedicine. *ACS Nano* **2025**, *19*, 18889−18901.
(50) Mirkin, C. A.; Letsinger, R. L.; Mucic, R. C.; Storhoff, J. J. A DNA-Based Method for Rationally Assembling Nanoparticles into Macroscopic Materials. *Nature* **1996**, *382*, 607−609.
(51) Mirkin, C. A.; Petrosko, S. H. Inspired beyond Nature: Three Decades of Spherical Nucleic Acids and Colloidal Crystal Engineering with DNA. *ACS Nano* **2023**, *17*, 16291−16307.
(52) Abraham, S. A.; Waterhouse, D. N.; Mayer, L. D.; Cullis, P. R.; Madden, T. D.; Bally, M. B. The Liposomal Formulation of Doxorubicin. In *Methods in Enzymology*, Vol. *391*; Elsevier, 2005; pp 71−97.
(53) Kaur, I. P.; Bhandari, R.; Bhandari, S.; Kakkar, V. Potential of Solid Lipid Nanoparticles in Brain Targeting. *J. Contr. Release* **2008**, *127*, 97−109.
(54) Farokhzad, O. C.; Langer, R. Impact of Nanotechnology on Drug Delivery. *ACS Nano* **2009**, *3*, 16−20.
(55) Lai, S. K.; Wang, Y. Y.; Hanes, J. Mucus-Penetrating Nanoparticles for Drug and Gene Delivery to Mucosal Tissues. *Adv. Drug. Delivery Rev.* **2009**, *61*, 158−171.
(56) Shi, J.; Votruba, A. R.; Farokhzad, O. C.; Langer, R. Nanotechnology in Drug Delivery and Tissue Engineering: From Discovery to Applications. *Nano Lett.* **2010**, *10*, 3223−3230.
(57) Barenholz, Y. Doxil(R)-the First FDA-Approved Nano-Drug: Lessons Learned. *J. Contr. Release* **2012**, *160*, 117−134.
(58) Shi, J.; Kantoff, P. W.; Wooster, R.; Farokhzad, O. C. Cancer Nanomedicine: Progress, Challenges and Opportunities. *Nat. Rev. Cancer* **2017**, *17*, 20−37.
(59) Adams, D.; Gonzalez-Duarte, A.; O'Riordan, W. D.; Yang, C. C.; Ueda, M.; Kristen, A. V.; Tournev, I.; Schmidt, H. H.; Coelho, T.; Berk, J. L.; Lin, K. P.; Vita, G.; Attarian, S.; Plante-Bordeneuve, V.; Mezei, M. M.; Campistol, J. M.; Buades, J.; Brannagan, T. H., 3rd; Kim, B. J.; Oh, J.; et al. Patisiran, an RNAi Therapeutic, for Hereditary Transthyretin Amyloidosis. *NEJM* **2018**, *379*, 11−21.
(60) Zhang, Z.; Wang, H.; Tan, T.; Li, J.; Wang, Z.; Li, Y. Rational Design of Nanoparticles with Deep Tumor Penetration for Effective Treatment of Tumor Metastasis. *Adv. Funct. Mater.* **2018**, *28*, 1801840.
(61) Wang, S.; Qin, L.; Yamankurt, G.; Skakuj, K.; Huang, Z.; Chen, P. C.; Dominguez, D.; Lee, A.; Zhang, B.; Mirkin, C. A. Rational Vaccinology with Spherical Nucleic Acids. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116*, 10473−10481.
(62) Polack, F. P.; Thomas, S. J.; Kitchin, N.; Absalon, J.; Gurtman, A.; Lockhart, S.; Perez, J. L.; Perez Marc, G.; Moreira, E. D.; Zerbini, C.; Bailey, R.; Swanson, K. A.; Roychoudhury, S.; Koury, K.; Li, P.; Kalina, W. V.; Cooper, D.; Frenck, R. W., Jr; Hammitt, L. L.; Tureci, O.; et al. Safety and Efficacy of the BNT162b2 mRNA Covid-19 Vaccine. *NEJM* **2020**, *383*, 2603−2615.
(63) Meng, T.; Zheng, J.; Chen, M.; Wang, B.; Luo, L.; Kulkarni, V.; Zhao, Y.; Stark, W. J.; Hanes, J.; Xu, Q. Subconjunctival Nanoparticle as a Long-Lasting Therapy for Corneal Diseases. *Toxicol. Lett.* **2020**, *331*, 12.
(64) Huang, Z.; Callmann, C. E.; Wang, S.; Vasher, M. K.; Evangelopoulos, M.; Petrosko, S. H.; Mirkin, C. A. Rational

Vaccinology: Harnessing Nanoscale Chemical Design for Cancer Immunotherapy. *ACS Cent. Sci.* **2022**, *8*, 692−704.
(65) Teplensky, M. H.; Evangelopoulos, M.; Dittmar, J. W.; Forsyth, C. M.; Sinegra, A. J.; Wang, S.; Mirkin, C. A. Multi-Antigen Spherical Nucleic Acid Cancer Vaccines. *Nat. Biomed. Eng.* **2023**, *7*, 911−927.
(66) Sridhar, S.; Modica, J. A.; Sykora, D. J.; Berns, E. J.; Mrksich, M. Synthesis and Activity of T-Cell Tumor-Directing MegaMolecules. *J. Am. Chem. Soc.* **2024**, *146*, 26801−26807.
(67) Zhang, Y. N.; Poon, W.; Tavares, A. J.; McGilvray, I. D.; Chan, W. C. W. Nanoparticle-Liver Interactions: Cellular Uptake and Hepatobiliary Elimination. *J. Contr. Release* **2016**, *240*, 332−348.
(68) Suk, J. S.; Xu, Q.; Kim, N.; Hanes, J.; Ensign, L. M. PEGylation as a strategy for improving nanoparticle-based drug and gene delivery. *Advanced Drug Delivery Reviews* **2016**, *99*, 28−51.
(69) Wartlick, H.; Michaelis, K.; Balthasar, S.; Strebhardt, K.; Kreuter, J.; Langer, K. Highly Specific HER2-Mediated Cellular Uptake of Antibody-Modified Nanoparticles in Tumor Cells. *J. Drug Target* **2004**, *12*, 461−471.
(70) Farokhzad, O. C.; Cheng, J.; Teply, B. A.; Sherifi, I.; Jon, S.; Kantoff, P. W.; Richie, J. P.; Langer, R. Targeted Nanoparticle-Aptamer Bioconjugates for Cancer Chemotherapy *in vivo*. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 6315−6320.
(71) Cutler, J. I.; Auyeung, E.; Mirkin, C. A. Spherical Nucleic Acids. *J. Am. Chem. Soc.* **2012**, *134*, 1376−1391.
(72) Blanco, E.; Shen, H.; Ferrari, M. Principles of Nanoparticle Design for Overcoming Biological Barriers to Drug Delivery. *Nat. Biotechnol.* **2015**, *33*, 941−951.
(73) Korin, E.; Bejerano, T.; Cohen, S. GalNAc Bio-Functionalization of Nanoparticles Assembled by Electrostatic Interactions Improves siRNA Targeting to the Liver. *J. Contr. Release* **2017**, *266*, 310−320.
(74) Fang, R. H.; Kroll, A. V.; Gao, W.; Zhang, L. Cell Membrane Coating Nanotechnology. *Adv. Mater.* **2018**, *30*, 1706759.
(75) Hadjesfandiari, N.; Parambath, A. 13 - Stealth Coatings for Nanoparticles: Polyethylene Glycol Alternatives. In *Engineering of Biomaterials for Drug Delivery Systems*, Parambath, A., Ed.; Woodhead Publishing, 2018; pp 345−361.
(76) Kusmierz, C. D.; Callmann, C. E.; Kudruk, S.; Distler, M. E.; Mirkin, C. A. Transferrin Aptamers Increase the In Vivo Blood-Brain Barrier Targeting of Protein Spherical Nucleic Acids. *Bioconjugate Chem.* **2022**, *33*, 1803−1810.
(77) Saha, T.; Fojtu, M.; Nagar, A. V.; Thurakkal, L.; Srinivasan, B. B.; Mukherjee, M.; Sibiyon, A.; Aggarwal, H.; Samuel, A.; Dash, C.; Jang, H. L.; Sengupta, S. Antibody Nanoparticle Conjugate-Based Targeted Immunotherapy for Non-Small Cell Lung Cancer. *Sci. Adv.* **2024**, *10*, eadi2046.
(78) Xia, C.; Cheng, H.; Hou, X.; Zhang, Y.; Zhou, X.; Yan, Q.; Cao, S. Spherical Nucleic Acids for Biomedical Applications. *ASEM* **2024**, *3*, 100117.
(79) Zamora, M. E.; Omo-Lamai, S.; Patel, M. N.; Wu, J.; Arguiri, E.; Muzykantov, V. R.; Myerson, J. W.; Marcos-Contreras, O. A.; Brenner, J. S. Combination of Physicochemical Tropism and Affinity Moiety Targeting of Lipid Nanoparticles Enhances Organ Targeting. *Nano Lett.* **2024**, *24*, 4774−4784.
(80) Cheng, Q.; Wei, T.; Farbiak, L.; Johnson, L. T.; Dilliard, S. A.; Siegwart, D. J. Selective Organ Targeting (SORT) Nanoparticles for Tissue-Specific mRNA Delivery and CRISPR-Cas Gene Editing. *Nat. Nanotechnol.* **2020**, *15*, 313−320.
(81) Dilliard, S. A.; Cheng, Q.; Siegwart, D. J. On the Mechanism of Tissue-Specific mRNA Delivery by Selective Organ Targeting Nanoparticles. *Proc. Natl. Acad. Sci. U.S.A.* **2021**, *118*, e2109256118.
(82) Dilliard, S. A.; Sun, Y.; Brown, M. O.; Sung, Y. C.; Chatterjee, S.; Farbiak, L.; Vaidya, A.; Lian, X.; Wang, X.; Lemoff, A.; Siegwart, D. J. The Interplay of Quaternary Ammonium Lipid Structure and Protein Corona on Lung-Specific mRNA Delivery by Selective Organ Targeting (SORT) Nanoparticles. *J. Contr. Release* **2023**, *361*, 361−372.
(83) Battistella, C.; Liang, Y.; Gianneschi, N. C. Innovations in Disease State Responsive Soft Materials for Targeting Extracellular Stimuli Associated with Cancer, Cardiovascular Disease, Diabetes, and Beyond. *Adv. Mater.* **2021**, *33*, 2007504.
(84) Skakuj, K.; Wang, S.; Qin, L.; Lee, A.; Zhang, B.; Mirkin, C. A. Conjugation Chemistry-Dependent T-Cell Activation with Spherical Nucleic Acids. *J. Am. Chem. Soc.* **2018**, *140*, 1227−1230.
(85) Dosta, P.; Cryer, A. M.; Dion, M. Z.; Shiraishi, T.; Langston, S. P.; Lok, D.; Wang, J.; Harrison, S.; Hatten, T.; Ganno, M. L.; Appleman, V. A.; Taboada, G. M.; Puigmal, N.; Ferber, S.; Kalash, S.; Prado, M.; Rodriguez, A. L.; Kamoun, W. S.; Abu-Yousif, A. O.; Artzi, N. Investigation of the Enhanced Antitumour Potency of STING Agonist after Conjugation to Polymer Nanoparticles. *Nat. Nanotechnol.* **2023**, *18*, 1351−1363.
(86) Sullivan, H. L.; Liang, Y.; Worthington, K.; Luo, C.; Gianneschi, N. C.; Christman, K. L. Enzyme-Responsive Nanoparticles for the Targeted Delivery of an MMP Inhibitor to Acute Myocardial Infarction. *Biomacromolecules* **2023**, *24*, 4695−4704.
(87) Dosta, P.; Dion, M. Z.; Prado, M.; Hurtado, P.; Riojas-Javelly, C. J.; Cryer, A. M.; Soria, Y.; Andrews Interiano, N.; Muñoz-Taboada, G.; Artzi, N. Matrix Metalloproteinase-and pH-Sensitive Nanoparticle System Enhances Drug Retention and Penetration in Glioblastoma. *ACS Nano* **2024**, *18*, 14145−14160.
(88) Tanita, K.; Koseki, Y.; Kumar, S.; Taemaitree, F.; Mizutani, A.; Nakatsuji, H.; Suzuki, R.; Dao, A. T. N.; Fujishima, F.; Tada, H.; Ishida, T.; Saijo, K.; Ishioka, C.; Kasai, H. Carrier-Free Nano-Prodrugs for Minimally Invasive Cancer Therapy. *Nanoscale* **2024**, *16*, 15256−15264.
(89) Paranandi, K. S.; Amar-Lewis, E.; Mirkin, C. A.; Artzi, N. Nomadic Nanomedicines: Medicines Enabled by the Paracrine Transfer Effect. *ACS Nano* **2025**, *19*, 21−30.
(90) Phillips, E.; Penate-Medina, O.; Zanzonico, P. B.; Carvajal, R. D.; Mohan, P.; Ye, Y.; Humm, J.; Gönen, M.; Kalaigian, H.; Schöder, H.; Strauss, H. W.; Larson, S. M.; Wiesner, U.; Bradbury, M. S. Clinical Translation of an Ultrasmall Inorganic Optical-PET Imaging Nanoparticle Probe. *Sci. Transl. Med.* **2014**, *6*, 260ra149−260ra149.
(91) Yu, M.; Xu, J.; Zheng, J. Renal Clearable Luminescent Gold Nanoparticles: From the Bench to the Clinic. *Angew. Chem. Int. Ed.* **2019**, *58*, 4112−4128.
(92) Choi, W.; Fattah, M.; Shang, Y.; Thompson, M. P.; Carrow, K. P.; Hu, D.; Liu, Z.; Avram, M. J.; Bailey, K.; Berger, O.; Qi, X.; Gianneschi, N. C. Proteomimetic Polymer Blocks Mitochondrial Damage, Rescues Huntington's Neurons, and Slows Onset of Neuropathology *in vivo*. *Sci. Adv.* **2024**, *10*, eado8307.
(93) Mesfin, J. M.; Carrow, K. P.; Chen, A.; Hopps, M. P.; Holm, J. J.; Lyons, Q. P.; Nguyen, M. B.; Hunter, J. D.; Magassa, A.; Wong, E. G.; Reimold, K.; Paleti, S. N.; Gardner, E.; Thompson, M. P.; Luo, C. G.; Zhang, X.; Christman, K. L.; Gianneschi, N. C. Protein-Like Polymers Targeting Keap1/Nrf2 as Therapeutics for Myocardial Infarction. *Adv. Mater.* **2025**, *37*, 2417885.
(94) Merkel, T. J.; Jones, S. W.; Herlihy, K. P.; Kersey, F. R.; Shields, A. R.; Napier, M.; Luft, J. C.; Wu, H.; Zamboni, W. C.; Wang, A. Z.; Bear, J. E.; DeSimone, J. M. Using Mechanobiological Mimicry of Red Blood Cells to Extend Circulation times of Hydrogel Microparticles. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108*, 586−591.
(95) Fang, R. H.; Hu, C. M.; Zhang, L. Nanoparticles Disguised as Red Blood Cells to Evade the Immune System. *Expert Opin. Biol. Ther.* **2012**, *12*, 385−389.
(96) Huang, K.; Ma, H.; Liu, J.; Huo, S.; Kumar, A.; Wei, T.; Zhang, X.; Jin, S.; Gan, Y.; Wang, P. C.; He, S.; Zhang, X.; Liang, X.-J. Size-Dependent Localization and Penetration of Ultrasmall Gold Nanoparticles in Cancer Cells, Multicellular Spheroids, and Tumors *in vivo*. *ACS Nano* **2012**, *6*, 4483−4493.
(97) Ben-Akiva, E.; Meyer, R. A.; Yu, H.; Smith, J. T.; Pardoll, D. M.; Green, J. J. Biomimetic Anisotropic Polymeric Nanoparticles Coated with Red Blood Cell Membranes for Enhanced Circulation and Toxin Removal. *Sci. Adv.* **2020**, *6*, eaay9035.
(98) Shields, C. W.; Evans, M. A.; Wang, L. L.-W.; Baugh, N.; Iyer, S.; Wu, D.; Zhao, Z.; Pusuluri, A.; Ukidve, A.; Pan, D. C.; Mitragotri, S. Cellular Backpacks for Macrophage Immunotherapy. *Sci. Adv.* **2020**, *6*, eaaz6579.

(99) Callmann, C. E.; Vasher, M. K.; Das, A.; Kusmierz, C. D.; Mirkin, C. A. *in vivo* Behavior of Ultrasmall Spherical Nucleic Acids. *Small* **2023**, *19*, 2300097.
(100) Peppas, N. Intelligent Therapeutics: Biomimetic Systems and Nanotechnology in Drug Delivery. *Adv. Drug Delivery Rev.* **2004**, *56*, 1529−1531.
(101) Peppas, N. A.; Hilt, J. Z.; Khademhosseini, A.; Langer, R. Hydrogels in Biology and Medicine: From Molecular Principles to Bionanotechnology. *Adv. Mater.* **2006**, *18*, 1345−1360.
(102) Cisneros, E.; Sherwani, N.; Lanier, O. L.; Peppas, N. A. Targeted Delivery Methods for RNA Interference are Necessary to Obtain a Potential Functional Cure for HIV/AIDS. *Adv. Drug Delivery Rev.* **2023**, *199*, 114970.
(103) Bahrami, K.; Lee, E.; Morse, B.; Lanier, O. L.; Peppas, N. A. Design of Nanoparticle-Based Systems for the Systemic Delivery of Chemotherapeutics: Alternative Potential Routes *via* Sublingual and Buccal Administration for Systemic Drug Delivery. *Drug Delivery Transl. Res.* **2024**, *14*, 1173−1188.
(104) Pérez-Herrero, E.; Lanier, O. L.; Krishnan, N.; D'Andrea, A.; Peppas, N. A. Drug Delivery Methods for Cancer Immunotherapy. *Drug Delivery Transl. Res.* **2024**, *14*, 30−61.
(105) Advanced Information, 2025. *NobelPrize.org*. https://www.nobelprize.org/prizes/chemistry/2024/advanced-information (accessed 2025 January 30).
(106) Nel, A. E.; Mädler, L.; Velegol, D.; Xia, T.; Hoek, E. M. V.; Somasundaran, P.; Klaessig, F.; Castranova, V.; Thompson, M. Understanding Biophysicochemical Interactions at the Nano-Bio Interface. *Nat. Mater.* **2009**, *8*, 543−557.
(107) Cha, M.; Emre, E. S. T.; Xiao, X.; Kim, J.-Y.; Bogdan, P.; VanEpps, J. S.; Violi, A.; Kotov, N. A. Unifying Structural Descriptors for Biological and Bioinspired Nanoscale Complexes. *Nat. Comput. Sci.* **2022**, *2*, 243−252.
(108) Xie, X.; Yu, T.; Li, X.; Zhang, N.; Foster, L. J.; Peng, C.; Huang, W.; He, G. Recent Advances in Targeting the "Undruggable" Proteins: From Drug Discovery to Clinical Trials. *Signal Transduct. Target. Ther.* **2023**, *8*, 335.
(109) Khripin, C. Y.; Pristinski, D.; Dunphy, D. R.; Brinker, C. J.; Kaehr, B. Protein-Directed Assembly of Arbitrary Three-Dimensional Nanoporous Silica Architectures. *ACS Nano* **2011**, *5*, 1401−1409.
(110) Kaehr, B.; Townson, J. L.; Kalinich, R. M.; Awad, Y. H.; Swartzentruber, B. S.; Dunphy, D. R.; Brinker, C. J. Cellular Complexity Captured in Durable Silica Biocomposites. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109*, 17336−17341.
(111) Townson, J. L.; Lin, Y.-S.; Chou, S. S.; Awad, Y. H.; Coker, E. N.; Brinker, C. J.; Kaehr, B. Synthetic Fossilization of Soft Biological Tissues and their Shape-preserving Transformation into Silica or Electron-Conductive Replicas. *Nat. Commun.* **2014**, *5*, 5665.
(112) Lei, Q.; Guo, J.; Kong, F.; Cao, J.; Wang, L.; Zhu, W.; Brinker, C. J. Bioinspired Cell Silicification: From Extracellular to Intracellular. *J. Am. Chem. Soc.* **2021**, *143*, 6305−6322.
(113) Dou, M.; Lu, C.; Rao, W. Bioinspired Materials and Technology for Advanced Cryopreservation. *Trends Biotechnol* **2022**, *40*, 93−106.
(114) Guo, J.; Amini, S.; Lei, Q.; Ping, Y.; Agola, J. O.; Wang, L.; Zhou, L.; Cao, J.; Franco, S.; Noureddine, A.; Miserez, A.; Zhu, W.; Brinker, C. J. Robust and Long-Term Cellular Protein and Enzymatic Activity Preservation in Biomineralized Mammalian Cells. *ACS Nano* **2022**, *16*, 2164−2175.
(115) Guo, J.; De May, H.; Franco, S.; Noureddine, A.; Tang, L.; Brinker, C. J.; Kusewitt, D. F.; Adams, S. F.; Serda, R. E. Cancer Vaccines from Cryogenically Silicified Tumour Cells Functionalized with Pathogen-Associated Molecular Patterns. *Nat. Biomed. Eng.* **2022**, *6*, 19−31.
(116) Zhou, L.; Lei, Q.; Guo, J.; Gao, Y.; Shi, J.; Yu, H.; Yin, W.; Cao, J.; Xiao, B.; Andreo, J.; Ettlinger, R.; Brinker, J. C.; Wuttke, S.; Zhu, W. Long-Term Whole Blood DNA Preservation by Cost-Efficient Cryosilicification. *Nat. Commun.* **2022**, *13*, 6265.
(117) Guo, S.; Brinker, C. J.; Zhu, W. Freezing Life within Refractory, Amorphous Silicon Dioxide. *Nat. Rev. Bioeng.* **2024**, *2*, 282−283.
(118) Liang, K.; Zhou, L.; Lei, Q.; Ruan, T.; Zhang, M.; Guo, J.; Brinker, C. J.; Zhu, W. Deep Silicification-Assisted Long-Term Preservation of Structural and Genomic Information Across Biospecies: From Micro to Macro. *Proc. Natl. Acad. Sci. U.S.A.* **2024**, *121*, e2408273121.
(119) Kim, J.; Lee, S.; Choi, J.; Baek, K.; Shim, T. S.; Hyun, J. K.; Park, S.-J. Shape-Changing DNA-Linked Nanoparticle Films Dictated by Lateral and Vertical Patterns. *Adv. Mater.* **2022**, *34*, 2109091.
(120) Ko, J.; Kim, J.; Ki, K.; Moon, S.; Jeon, H.; Park, J. H.; Golla, M.; Chun, C. J.; Kim, J. S.; Lee, A.; Kim, H.; Park, S. S.; Shim, T. S.; Park, S.-J. Shape-Dependent Locomotion of DNA-Linked Magnetic Nanoparticle Films. *Nano Lett.* **2025**, *25*, 419−425.
(121) Schultz, J. D.; Yuly, J. L.; Arsenault, E. A.; Parker, K.; Chowdhury, S. N.; Dani, R.; Kundu, S.; Nuomin, H.; Zhang, Z.; Valdiviezo, J.; Zhang, P.; Orcutt, K.; Jang, S. J.; Fleming, G. R.; Makri, N.; Ogilvie, J. P.; Therien, M. J.; Wasielewski, M. R.; Beratan, D. N. Coherence in Chemistry: Foundations and Frontiers. *Chem. Rev.* **2024**, *124*, 11641−11766.
(122) Zheng, Z.; Zu, X.; Zhang, Y.; Zhou, W. Rational Design of Type-II Nano-Heterojunctions for Nanoscale Optoelectronics. *Mater. Today Phys.* **2020**, *15*, 100262.
(123) Scanlon, D. O.; Dunnill, C. W.; Buckeridge, J.; Shevlin, S. A.; Logsdail, A. J.; Woodley, S. M.; Catlow, C. R. A.; Powell, M. J.; Palgrave, R. G.; Parkin, I. P.; Watson, G. W.; Keal, T. W.; Sherwood, P.; Walsh, A.; Sokol, A. A. Band Alignment of Rutile and Anatase TiO_2. *Nat. Mater.* **2013**, *12*, 798−801.
(124) Huang, H.; Yuan, H.; Janssen, K. P. F.; Solís-Fernández, G.; Wang, Y.; Tan, C. Y. X.; Jonckheere, D.; Debroye, E.; Long, J.; Hendrix, J.; Hofkens, J.; Steele, J. A.; Roeffaers, M. B. J. Efficient and Selective Photocatalytic Oxidation of Benzylic Alcohols with Hybrid Organic-Inorganic Perovskite Materials. *ACS Energy Lett.* **2018**, *3*, 755−759.
(125) Huang, H.; Yuan, H.; Zhao, J.; Solís-Fernández, G.; Zhou, C.; Seo, J. W.; Hendrix, J.; Debroye, E.; Steele, J. A.; Hofkens, J.; Long, J.; Roeffaers, M. B. J. C(sp3)-H Bond Activation by Perovskite Solar Photocatalyst Cell. *ACS Energy Lett.* **2019**, *4*, 203−208.
(126) Kum, H.; Lee, D.; Kong, W.; Kim, H.; Park, Y.; Kim, Y.; Baek, Y.; Bae, S.-H.; Lee, K.; Kim, J. Epitaxial Growth and Layer-Transfer Techniques for Heterogeneous Integration of Materials for Electronic and Photonic Devices. *Nat. Electron.* **2019**, *2*, 439−450.
(127) Liu, H.; Tan, Y.; Cao, M.; Hu, H.; Wu, L.; Yu, X.; Wang, L.; Sun, B.; Zhang, Q. Fabricating $CsPbX_3$-Based Type I and Type II Heterostructures by Tuning the Halide Composition of Janus $CsPbX_3/ZrO_2$ Nanocrystals. *ACS Nano* **2019**, *13*, 5366−5374.
(128) Huang, H.; Verhaeghe, D.; Weng, B.; Ghosh, B.; Zhang, H.; Hofkens, J.; Steele, J. A.; Roeffaers, M. B. J. Metal Halide Perovskite Based Heterojunction Photocatalysts. *Angew. Chem. Int. Ed.* **2022**, *61*, e202203261.
(129) Berera, R.; van Grondelle, R.; Kennis, J. T. M. Ultrafast Transient Absorption Spectroscopy: Principles and Application to Photosynthetic Systems. *Photosynth. Res.* **2009**, *101*, 105−118.
(130) Manaka, T.; Iwamoto, M. Optical Second-Harmonic Generation Measurement for Probing Organic Device Operation. *Light Sci. Appl.* **2016**, *5*, e16040.
(131) Bettis Homan, S.; Sangwan, V. K.; Balla, I.; Bergeron, H.; Weiss, E. A.; Hersam, M. C. Ultrafast Exciton Dissociation and Long-Lived Charge Separation in a Photovoltaic Pentacene-MoS_2 van der Waals Heterojunction. *Nano Lett.* **2017**, *17*, 164−169.
(132) Gaynor, J. D.; Fidler, A. P.; Lin, Y.-C.; Chang, H.-T.; Zuerch, M.; Neumark, D. M.; Leone, S. R. Solid State Core-Exciton Dynamics in NaCl Observed by Tabletop Attosecond Four-Wave Mixing Spectroscopy. *Phys. Rev. B* **2021**, *103*, 245140.
(133) Speelman, R.; Marker, E. J.; Geiger, F. M. Quantifying Stern Layer Water Alignment Before and During the Oxygen Evolution Reaction. *Sci. Adv.* **2025**, *11*, eado8536.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

(134) Gaynor, J. D.; Fidler, A. P.; Kobayashi, Y.; Lin, Y.-C.; Keenan, C. L.; Neumark, D. M.; Leone, S. R. Nonresonant Coherent Amplitude Transfer in Attosecond Four-Wave-Mixing Spectroscopy. *Phys. Rev. A* **2023**, *107*, 023526.

(135) Moore, A. M.; Yeganeh, S.; Yao, Y.; Claridge, S. A.; Tour, J. M.; Ratner, M. A.; Weiss, P. S. Polarizabilities of Adsorbed and Assembled Molecules: Measuring the Conductance through Buried Contacts. *ACS Nano* **2010**, *4*, 7630−7636.

(136) Claridge, S. A.; Schwartz, J. J.; Weiss, P. S. Electrons, Photons, and Force: Quantitative Single-Molecule Measurements from Physics to Biology. *ACS Nano* **2011**, *5*, 693−729.

(137) Bonnell, D. A.; Basov, D. N.; Bode, M.; Diebold, U.; Kalinin, S. V.; Madhavan, V.; Novotny, L.; Salmeron, M.; Schwarz, U. D.; Weiss, P. S. Imaging Physical Phenomena with Local Probes: From Electrons to Photons. *Rev. Mod. Phys.* **2012**, *84*, 1343−1381.

(138) Kim, J.; Rim, Y. S.; Liu, Y.; Serino, A. C.; Thomas, J. C.; Chen, H.; Yang, Y.; Weiss, P. S. Interface Control in Organic Electronics Using Mixed Monolayers of Carboranethiol Isomers. *Nano Lett.* **2014**, *14*, 2946−2951.

(139) Scheuerer, P.; Patera, L. L.; Simbürger, F.; Queck, F.; Swart, I.; Schuler, B.; Gross, L.; Moll, N.; Repp, J. Charge-Induced Structural Changes in a Single Molecule Investigated by Atomic Force Microscopy. *Phys. Rev. Lett.* **2019**, *123*, 066001.

(140) Barr, K. K.; Chiang, N.; Bertozzi, A. L.; Gilles, J.; Osher, S. J.; Weiss, P. S. Extraction of Hidden Science from Nanoscale Images. *J. Phys. Chem. C* **2022**, *126*, 3−13.

(141) Kaiser, K.; Lieske, L.-A.; Repp, J.; Gross, L. Charge-State Lifetimes of Single Molecules on Few Monolayers of NaCl. *Nat. Commun.* **2023**, *14*, 4988.

(142) Swearer, D. F.; Bourgeois, B. B.; Angell, D. K.; Dionne, J. A. Advancing Plasmon-Induced Selectivity in Chemical Transformations with Optically Coupled Transmission Electron Microscopy. *Acc. Chem. Res.* **2021**, *54*, 3632−3642.

(143) Hassan, M. T.; Baskin, J. S.; Liao, B.; Zewail, A. H. High-Temporal-Resolution Electron Microscopy for Imaging Ultrafast Electron Dynamics. *Nat. Photonics* **2017**, *11*, 425−430.

(144) Yannai, M.; Dahan, R.; Gorlach, A.; Adiv, Y.; Wang, K.; Madan, I.; Gargiulo, S.; Barantani, F.; Dias, E. J. C.; Vanacore, G. M.; Rivera, N.; Carbone, F.; García de Abajo, F. J.; Kaminer, I. Ultrafast Electron Microscopy of Nanoscale Charge Dynamics in Semiconductors. *ACS Nano* **2023**, *17*, 3645−3656.

(145) Xu, C.; Barden, N.; Alexeev, E. M.; Wang, X.; Long, R.; Cadore, A. R.; Paradisanos, I.; Ott, A. K.; Soavi, G.; Tongay, S.; Cerullo, G.; Ferrari, A. C.; Prezhdo, O. V.; Loh, Z.-H. Ultrafast Charge Transfer and Recombination Dynamics in Monolayer-Multilayer WSe_2 Junctions Revealed by Time-Resolved Photoemission Electron Microscopy. *ACS Nano* **2024**, *18*, 1931−1947.

(146) Winkler, F.; Barthel, J.; Dunin-Borkowski, R. E.; Müller-Caspary, K. Direct Measurement of Electrostatic Potentials at the Atomic Scale: A Conceptual Comparison between Electron Holography and Scanning Transmission Electron Microscopy. *Ultramicroscopy* **2020**, *210*, 112926.

(147) Aso, R.; Midoh, Y.; Tanigaki, T.; Murakami, Y. High-Precision Charge Analysis in a Catalytic Nanoparticle by Electron Holography. *Microscopy* **2024**, *73*, 301−307.

(148) Piner, R. D.; Zhu, J.; Xu, F.; Hong, S.; Mirkin, C. A. "Dip-Pen" Nanolithography. *Science* **1999**, *283*, 661−663.

(149) Huo, F. W.; Zheng, Z. J.; Zheng, G. F.; Giam, L. R.; Zhang, H.; Mirkin, C. A. Polymer Pen Lithography. *Science* **2008**, *321*, 1658−1660.

(150) Zhang, L.; Xia, Y. Scaling Up the Production of Colloidal Nanocrystals: Should We Increase or Decrease the Reaction Volume? *Adv. Mater.* **2014**, *26*, 2600−2606.

(151) Du, J. S.; Shin, D.; Stanev, T. K.; Musumeci, C.; Xie, Z.; Huang, Z.; Lai, M.; Sun, L.; Zhou, W.; Stern, N. P.; Dravid, V. P.; Mirkin, C. A. Halide Perovskite Nanocrystal Arrays: Multiplexed Synthesis and Size-Dependent Emission. *Sci. Adv.* **2020**, *6*, eabc4959.

(152) Liu, G.; Petrosko, S. H.; Zheng, Z.; Mirkin, C. A. Evolution of Dip-Pen Nanolithography (DPN): From Molecular Patterning to Materials Discovery. *Chem. Rev.* **2020**, *120*, 6009−6047.

(153) Abdel-Latif, K.; Epps, R. W.; Bateni, F.; Han, S.; Reyes, K. G.; Abolhasani, M. Self-Driven Multistep Quantum Dot Synthesis Enabled by Autonomous Robotic Experimentation in Flow. *Adv. Intelligent Sys.* **2021**, *3*, 2000245.

(154) Dhiman, S.; Joshi, R. S.; Singh, S.; Gill, S. S.; Singh, H.; Kumar, R.; Kumar, V. A Framework for Effective and Clean Conversion of Machining Waste into Metal Powder Feedstock for Additive Manufacturing. *Cleaner Engin. Technol.* **2021**, *4*, 100151.

(155) Macfarlane, R. J. From Nano to Macro: Thinking Bigger in Nanoparticle Assembly. *Nano Lett.* **2021**, *21*, 7432−7434.

(156) Lai, M.; Shin, D.; Jibril, L.; Mirkin, C. A. Combinatorial Synthesis and Screening of Mixed Halide Perovskite Megalibraries. *J. Am. Chem. Soc.* **2022**, *144*, 13823−13830.

(157) Li, H.; Li, H.; Lai, Y.; Yang, Z.; Yang, Q.; Liu, Y.; Zheng, Z.; Liu, Y.; Sun, Y.; Zhong, B.; Wu, Z.; Guo, X. Revisiting the Preparation Progress of Nano-Structured Si Anodes toward Industrial Application from the Perspective of Cost and Scalability. *Adv. Energy Mater.* **2022**, *12*, 2102181.

(158) Shin, D.; Lai, M.; Shin, Y.; Du, J. S.; Jibril, L.; Rondinelli, J. M.; Mirkin, C. A. From Heterostructures to Solid-Solutions: Structural Tunability in Mixed Halide Perovskites. *Adv. Mater.* **2023**, *35*, 2205923.

(159) Smith, P. T.; Wahl, C. B.; Orbeck, J. K. H.; Mirkin, C. A. Megalibraries: Supercharged Acceleration of Materials Discovery. *MRS Bull.* **2023**, *48*, 1172−1183.

(160) Smith, P. T.; Ye, Z.; Pietryga, J.; Huang, J.; Wahl, C. B.; Hedlund Orbeck, J. K.; Mirkin, C. A. Molecular Thin Films Enable the Synthesis and Screening of Nanoparticle Megalibraries Containing Millions of Catalysts. *J. Am. Chem. Soc.* **2023**, *145*, 14031−14043.

(161) Cai, T.; Shin, D.; Li, J.; Xu, D. D.; Pietryga, J.; Zhang, Y.; Mirkin, C. A. Creating Chromaticity Palettes and Identifying White Light Emitters through Nanocrystal Megalibraries. *Sci. Adv.* **2025**, *11*, eads4453.

(162) Santos, P. J.; Gabrys, P. A.; Zornberg, L. Z.; Lee, M. S.; Macfarlane, R. J. Macroscopic Materials Assembled from Nanoparticle Superlattices. *Nature* **2021**, *591*, 586−591.

(163) Park, K.; Steingass, K.; Fontana, J.; Vaia, R. Absorptive Optical Filters and Polarizers through Multiplexing and Reshaping of Low-Polydispersity Plasmonic Nanorods. *ACS Appl. Mater. Interfaces* **2025**, *17*, 36069−36080.

(164) Puntes, V. F.; Gorostiza, P.; Aruguete, D. M.; Bastus, N. G.; Alivisatos, A. P. Collective Behavior in two-Dimensional Cobalt Nanoparticle Assemblies Observed by Magnetic Force Microscopy. *Nat. Mater.* **2004**, *3*, 263−268.

(165) Shevchenko, E. V.; Talapin, D. V.; Kotov, N. A.; O'Brien, S.; Murray, C. B. Structural Diversity in Binary Nanoparticle Superlattices. *Nature* **2006**, *439*, 55−59.

(166) Chen, J.; Dong, A.; Cai, J.; Ye, X.; Kang, Y.; Kikkawa, J. M.; Murray, C. B. Collective Dipolar Interactions in Self-Assembled Magnetic Binary Nanocrystal Superlattice Membranes. *Nano Lett.* **2010**, *10*, 5103−5108.

(167) Nie, Z.; Petukhova, A.; Kumacheva, E. Properties and Emerging Applications of Self-Assembled Structures Made from Inorganic Nanoparticles. *Nat. Nanotechnol.* **2010**, *5*, 15−25.

(168) Talapin, D. V.; Lee, J.-S.; Kovalenko, M. V.; Shevchenko, E. V. Prospects of Colloidal Nanocrystals for Electronic and Optoelectronic Applications. *Chem. Rev.* **2010**, *110*, 389−458.

(169) Tang, J.; Kemp, K. W.; Hoogland, S.; Jeong, K. S.; Liu, H.; Levina, L.; Furukawa, M.; Wang, X.; Debnath, R.; Cha, D.; Chou, K. W.; Fischer, A.; Amassian, A.; Asbury, J. B.; Sargent, E. H. Colloidal-Quantum-Dot Photovoltaics Using Atomic-Ligand Passivation. *Nat. Mater.* **2011**, *10*, 765−771.

(170) Boles, M. A.; Ling, D.; Hyeon, T.; Talapin, D. V. The Surface Science of Nanocrystals. *Nat. Mater.* **2016**, *15*, 141−153.

(171) Seo, S. E.; Li, T.; Senesi, A. J.; Mirkin, C. A.; Lee, B. The Role of Repulsion in Colloidal Crystal Engineering with DNA. *J. Am. Chem. Soc.* **2017**, *139*, 16528−16535.
(172) Seo, S. E.; Girard, M.; Olvera de la Cruz, M.; Mirkin, C. A. Non-Equilibrium Anisotropic Colloidal Single Crystal Growth with DNA. *Nature Commun.* **2018**, *9*, 4558.
(173) Gabrys, P. A.; Zornberg, L. Z.; Macfarlane, R. J. Programmable Atom Equivalents: Atomic Crystallization as a Framework for Synthesizing Nanoparticle Superlattices. *Small* **2019**, *15*, 1805424.
(174) Lewis, D. J.; Carter, D. J. D.; Macfarlane, R. J. Using DNA to Control the Mechanical Response of Nanoparticle Superlattices. *J. Am. Chem. Soc.* **2020**, *142*, 19181−19188.
(175) Santos, P. J.; Macfarlane, R. J. Reinforcing Supramolecular Bonding with Magnetic Dipole Interactions to Assemble Dynamic Nanoparticle Superlattices. *J. Am. Chem. Soc.* **2020**, *142*, 1170−1174.
(176) Cherniukh, I.; Rainò, G.; Stöferle, T.; Burian, M.; Travesset, A.; Naumenko, D.; Amenitsch, H.; Erni, R.; Mahrt, R. F.; Bodnarchuk, M. I.; Kovalenko, M. V. Perovskite-Type Superlattices from Lead Halide Perovskite Nanocubes. *Nature* **2021**, *593*, 535−542.
(177) Lee, M. S.; Yee, D. W.; Ye, M.; Macfarlane, R. J. Nanoparticle Assembly as a Materials Development Tool. *J. Am. Chem. Soc.* **2022**, *144*, 3330−3346.
(178) Li, R. L.; Thrasher, C. J.; Hueckel, T.; Macfarlane, R. J. Hierarchically Structured Nanocomposites *via* a "Systems Materials Science" Approach. *Acc. Mater. Res.* **2022**, *3*, 1248−1259.
(179) Hueckel, T.; Luo, X.; Aly, O. F.; Macfarlane, R. J. Nanoparticle Brushes: Macromolecular Ligands for Materials Synthesis. *Acc. Chem. Res.* **2023**, *56*, 1931−1941.
(180) Lewis, J. A.; Smay, J. E.; Stuecker, J.; Cesarano, J. Direct Ink Writing of Three-Dimensional Ceramic Structures. *J. Am. Ceram. Soc.* **2006**, *89*, 3599−3609.
(181) Walker, S. B.; Lewis, J. A. Reactive Silver Inks for Patterning High-Conductivity Features at Mild Temperatures. *J. Am. Chem. Soc.* **2012**, *134*, 1419−1421.
(182) Kagan, C. R.; Lifshitz, E.; Sargent, E. H.; Talapin, D. V. Building Devices from Colloidal Quantum Dots. *Science* **2016**, *353*, aac5523.
(183) Zornberg, L. Z.; Gabrys, P. A.; Macfarlane, R. J. Optical Processing of DNA-Programmed Nanoparticle Superlattices. *Nano Lett.* **2019**, *19*, 8074−8081.
(184) Lee, M. S.; Alexander-Katz, A.; Macfarlane, R. J. Nanoparticle Assembly in High Polymer Concentration Solutions Increases Superlattice Stability. *Small* **2021**, *17*, 2102107.
(185) Callister, W. D. *Materials Science and Engineering: An Introduction*; John Wiley and Sons, 2007.
(186) Hosford, W. F.; Caddell, R. M. *Metal Forming: Mechanics and Metallurgy*; Cambridge University Press, 2007. DOI: 10.1017/CBO9780511811111.
(187) Wang, M. X.; Seo, S. E.; Gabrys, P. A.; Fleischman, D.; Lee, B.; Kim, Y.; Atwater, H. A.; Macfarlane, R. J.; Mirkin, C. A. Epitaxy: Programmable Atom Equivalents Versus Atoms. *ACS Nano* **2017**, *11*, 180−185.
(188) Gabrys, P. A.; Macfarlane, R. J. Controlling Crystal Texture in Programmable Atom Equivalent Thin Films. *ACS Nano* **2019**, *13*, 8452−8460.
(189) Dhulipala, S.; Yee, D. W.; Zhou, Z.; Sun, R.; Andrade, J. E.; Macfarlane, R. J.; Portela, C. M. Tunable Mechanical Response of Self-Assembled Nanoparticle Superlattices. *Nano Lett.* **2023**, *23*, 5155−5163.
(190) Thrasher, C. J.; Murphy-Genao, N. J.; Sbalbi, N. A.; Li, R. L.; Hueckel, T.; Ye, M.; Hart, A. J.; Macfarlane, R. J. Forging Nanoparticle Superlattices with Colloidal Metallurgy. *ACS Nano* **2025**, *19*, 20753−20764.
(191) Alberts, B. The Cell as a Collection of Protein Machines: Preparing the Next Generation of Molecular Biologists. *Cell* **1998**, *92*, 291−294.
(192) Goodsell, D. S. *The Machinery of Life*; Copernicus, New York, 2009. DOI: 10.1007/978-0-387-84925-6.
(193) Zheludev, N. I.; Kivshar, Y. S. From Metamaterials to Metadevices. *Nat. Mater.* **2012**, *11*, 917−924.
(194) Bauer, H.; Burkacky, O.; Kenevan, P.; Lingemann, S.; Pototzky, K.; Wiseman, B. Semiconductor Design and Manufacturing: Achieving Leading-Edge Capabilities. Advanced Electronics Practice, 2020.
(195) Isaacoff, B. P.; Brown, K. A. Progress in Top-Down Control of Bottom-Up Assembly. *Nano Lett.* **2017**, *17*, 6508−6510.
(196) Tian, Y.; Wang, T.; Liu, W.; Xin, H. L.; Li, H.; Ke, Y.; Shih, W. M.; Gang, O. Prescribed Nanoparticle Cluster Architectures and Low-Dimensional Arrays Built Using Octahedral DNA Origami Frames. *Nat. Nanotechnol.* **2015**, *10*, 637−644.
(197) Choi, J.-H.; Wang, H.; Oh, S. J.; Paik, T.; Sung, P.; Sung, J.; Ye, X.; Zhao, T.; Diroll, B. T.; Murray, C. B.; Kagan, C. R. Exploiting the Colloidal Nanocrystal Library to Construct Electronic Devices. *Science* **2016**, *352*, 205−208.
(198) García-Lojo, D.; Núñez-Sánchez, S.; Gómez-Graña, S.; Grzelczak, M.; Pastoriza-Santos, I.; Pérez-Juste, J.; Liz-Marzán, L. M. Plasmonic Supercrystals. *Acc. Chem. Res.* **2019**, *52*, 1855−1864.
(199) Hens, Z.; De Roo, J. Atomically Precise Nanocrystals. *J. Am. Chem. Soc.* **2020**, *142*, 15627−15637.
(200) Kang, X.; Li, Y.; Zhu, M.; Jin, R. Atomically Precise Alloy Nanoclusters: Syntheses, Structures, and Properties. *Chem. Soc. Rev.* **2020**, *49*, 6443−6514.
(201) Zhou, W.; Liu, Z.; Huang, Z.; Lin, H.; Samanta, D.; Lin, Q.-Y.; Aydin, K.; Mirkin, C. A. Device-Quality, Reconfigurable Metamaterials from Shape-Directed Nanocrystal Assembly. *Proc. Natl. Acad. Sci. U.S.A.* **2020**, *117*, 21052−21057.
(202) Ward, L.; Agrawal, A.; Choudhary, A.; Wolverton, C. A General-Purpose Machine Learning Framework for Predicting Properties of Inorganic Materials. *npj Comput. Mater.* **2016**, *2*, 16028.
(203) Jumper, J.; Evans, R.; Pritzel, A.; Green, T.; Figurnov, M.; Ronneberger, O.; Tunyasuvunakool, K.; Bates, R.; Žídek, A.; Potapenko, A.; Bridgland, A.; Meyer, C.; Kohl, S. A. A.; Ballard, A. J.; Cowie, A.; Romera-Paredes, B.; Nikolov, S.; Jain, R.; Adler, J.; Back, T.; et al. Highly Accurate Protein Structure Prediction with AlphaFold. *Nature* **2021**, *596*, 583−589.
(204) Abriata, L. A. The Nobel Prize in Chemistry: Past, Present, and Future of AI in Biology. *Commun. Biol.* **2024**, *7*, 1409.
(205) Lemm, D.; von Rudorff, G. F.; von Lilienfeld, O. A. Machine Learning Based Energy-Free Structure Predictions of Molecules, Transition States, and Solids. *Nat. Commun.* **2021**, *12*, 4468.
(206) Jiang, C.; Marianetti, C. A.; Khafizov, M.; Hurley, D. H. Machine Learning Potential Assisted Exploration of Complex Defect Potential Energy Surfaces. *npj Comput. Mater.* **2024**, *10*, 21.
(207) Nandy, A.; Duan, C.; Kulik, H. J. Using Machine Learning and Data Mining to Leverage Community Knowledge for the Engineering of Stable Metal-Organic Frameworks. *J. Am. Chem. Soc.* **2021**, *143*, 17535−17547.
(208) Zheng, Z.; Zhang, O.; Borgs, C.; Chayes, J. T.; Yaghi, O. M. ChatGPT Chemistry Assistant for Text Mining and the Prediction of MOF Synthesis. *J. Am. Chem. Soc.* **2023**, *145*, 18048−18062.
(209) Tennyson, E. M.; Doherty, T. A. S.; Stranks, S. D. Heterogeneity at Multiple Length Scales in Halide Perovskite Semiconductors. *Nat. Rev. Mater.* **2019**, *4*, 573−587.
(210) Yao, Z.; Lum, Y.; Johnston, A.; Mejia-Mendoza, L. M.; Zhou, X.; Wen, Y.; Aspuru-Guzik, A.; Sargent, E. H.; Seh, Z. W. Machine Learning for a Sustainable Energy Future. *Nat. Rev. Mater.* **2023**, *8*, 202−215.
(211) Knoesel, E.; Hotzel, A.; Wolf, M. Ultrafast Dynamics of Hot Electrons and Holes in Copper: Excitation, Energy Relaxation, and Transport Effects. *Phys. Rev. B* **1998**, *57*, 12812−12824.
(212) Santos, E.; Schmickler, W. On the Timescale of Electrochemical Processes. *Electrochim. Acta* **2024**, *498*, 144659.
(213) Dong, B.; Pei, Y.; Zhao, F.; Goh, T. W.; Qi, Z.; Xiao, C.; Chen, K.; Huang, W.; Fang, N. *in situ* Quantitative Single-Molecule Study of Dynamic Catalytic Processes in Nanoconfinement. *Nat. Catal.* **2018**, *1*, 135−140.

(214) Yang, Y.; Louisia, S.; Yu, S.; Jin, J.; Roh, I.; Chen, C.; Fonseca Guzman, M. V.; Feijóo, J.; Chen, P.-C.; Wang, H.; Pollock, C. J.; Huang, X.; Shao, Y.-T.; Wang, C.; Muller, D. A.; Abruña, H. D.; Yang, P. Operando Studies Reveal Active Cu Nanograins for CO_2 Electroreduction. *Nature* **2023**, *614*, 262−269.
(215) Du, J. S.; Cherqui, C.; Ueltschi, T. W.; Wahl, C. B.; Bourgeois, M.; Van Duyne, R. P.; Schatz, G. C.; Dravid, V. P.; Mirkin, C. A. Discovering Polyelemental Nanostructures with Redistributed Plasmonic Modes through Combinatorial Synthesis. *Sci. Adv.* **2023**, *9*, eadj6129.
(216) Kim, Y.-J.; Nho, H.-W.; Ji, S.; Lee, H.; Ko, H.; Weissenrieder, J.; Kwon, O.-H. Femtosecond-Resolved Imaging of a Single-Particle Phase Transition in Energy-Filtered Ultrafast Electron Microscopy. *Sci. Adv.* **2023**, *9*, eadd5375.
(217) Zhang, A.; Lieber, C. M. Nano-Bioelectronics. *Chem. Rev.* **2016**, *116*, 215−257.
(218) Son, D.; Kang, J.; Vardoulis, O.; Kim, Y.; Matsuhisa, N.; Oh, J. Y.; To, J. W.; Mun, J.; Katsumata, T.; Liu, Y.; McGuire, A. F.; Krason, M.; Molina-Lopez, F.; Ham, J.; Kraft, U.; Lee, Y.; Yun, Y.; Tok, J. B.-H.; Bao, Z. An Integrated Self-Healable Electronic Skin System Fabricated *via* Dynamic Reconstruction of a Nanostructured Conducting Network. *Nat. Nanotechnol.* **2018**, *13*, 1057−1065.
(219) Cho, K. W.; Sunwoo, S.-H.; Hong, Y. J.; Koo, J. H.; Kim, J. H.; Baik, S.; Hyeon, T.; Kim, D.-H. Soft Bioelectronics Based on Nanomaterials. *Chem. Rev.* **2022**, *122*, 5068−5143.
(220) Luo, Y.; Abidian, M. R.; Ahn, J.-H.; Akinwande, D.; Andrews, A. M.; Antonietti, M.; Bao, Z.; Berggren, M.; Berkey, C. A.; Bettinger, C. J.; et al. Technology Roadmap for Flexible Sensors. *ACS Nano* **2023**, *17*, 5211−5295.
(221) Karatum, O.; Gwak, M.-J.; Hyun, J.; Onal, A.; Koirala, G. R.; Kim, T.-i.; Nizamoglu, S. Optical Neuromodulation at All Scales: From Nanomaterials to Wireless Optoelectronics and Integrated Systems. *Chem. Soc. Rev.* **2023**, *52*, 3326−3352.
(222) de Araujo, W. R.; Lukas, H.; Torres, M. D.; Gao, W.; de la Fuente-Nunez, C. Low-Cost Biosensor Technologies for Rapid Detection of COVID-19 and Future Pandemics. *ACS Nano* **2024**, *18*, 1757−1777.
(223) Nel, A.; Xia, T.; Madler, L.; Li, N. Toxic Potential of Materials at the Nanolevel. *Science* **2006**, *311*, 622−627.
(224) McClements, D. J.; Xiao, H. Is Nano Safe in Foods? Establishing the Factors Impacting the Gastrointestinal Fate and Toxicity of Organic and Inorganic Food-Grade Nanoparticles. *npj Sci. Food* **2017**, *1*, 6.
(225) Li, J.; Wang, X. Materials Perspectives for Self-Powered Cardiac Implantable Electronic Devices Toward Clinical Translation. *Acc. Mater. Res.* **2021**, *2*, 739−750.
(226) Yuk, H.; Lu, B.; Zhao, X. Hydrogel Bioelectronics. *Chem. Soc. Rev.* **2019**, *48*, 1642−1667.
(227) Fang, Y.; Yang, X.; Lin, Y.; Shi, J.; Prominski, A.; Clayton, C.; Ostroff, E.; Tian, B. Dissecting Biological and Synthetic Soft-Hard Interfaces for Tissue-Like Systems. *Chem. Rev.* **2022**, *122*, 5233−5276.
(228) Jiang, Y.; Ji, S.; Sun, J.; Huang, J.; Li, Y.; Zou, G.; Salim, T.; Wang, C.; Li, W.; Jin, H.; Xu, J.; Wang, S.; Lei, T.; Yan, X.; Peh, W. Y. X.; Yen, S.-C.; Liu, Z.; Yu, M.; Zhao, H.; Lu, Z.; Li, G.; Gao, H.; Liu, Z.; Bao, Z.; Chen, X. A Universal Interface for Plug-and-Play Assembly of Stretchable Devices. *Nature* **2023**, *614*, 456−462.
(229) Yi, J.; Zou, G.; Huang, J.; Ren, X.; Tian, Q.; Yu, Q.; Wang, P.; Yuan, Y.; Tang, W.; Wang, C.; Liang, L.; Cao, Z.; Li, Y.; Yu, M.; Jiang, Y.; Zhang, F.; Yang, X.; Li, W.; Wang, X.; Luo, Y.; Loh, X. J.; Li, G.; Hu, B.; Liu, Z.; Gao, H.; Chen, X. Water-Responsive Supercontractile Polymer Films for Bioelectronic Interfaces. *Nature* **2023**, *624*, 295−302.
(230) Miyamoto, A.; Lee, S.; Cooray, N. F.; Lee, S.; Mori, M.; Matsuhisa, N.; Jin, H.; Yoda, L.; Yokota, T.; Itoh, A.; Sekino, M.; Kawasaki, H.; Ebihara, T.; Amagai, M.; Someya, T. Inflammation-Free, Gas-Permeable, Lightweight, Stretchable On-Skin Electronics with Nanomeshes. *Nat. Nanotechnol.* **2017**, *12*, 907−913.
(231) Li, Q.; Chen, G.; Cui, Y.; Ji, S.; Liu, Z.; Wan, C.; Liu, Y.; Lu, Y.; Wang, C.; Zhang, N.; Cheng, Y.; Zhang, K.-Q.; Chen, X. Highly Thermal-Wet Comfortable and Conformal Silk-Based Electrodes for On-Skin Sensors with Sweat Tolerance. *ACS Nano* **2021**, *15*, 9955−9966.
(232) Huang, Q.; Zheng, Z. Pathway to Developing Permeable Electronics. *ACS Nano* **2022**, *16*, 15537−15544.
(233) Lee, S.; Liang, X.; Kim, J. S.; Yokota, T.; Fukuda, K.; Someya, T. Permeable Bioelectronics toward Biointegrated Systems. *Chem. Rev.* **2024**, *124*, 6543−6591.
(234) Zhuang, Q.; Yao, K.; Zhang, C.; Song, X.; Zhou, J.; Zhang, Y.; Huang, Q.; Zhou, Y.; Yu, X.; Zheng, Z. Permeable, Three-Dimensional Integrated Electronic Skins with Stretchable Hybrid Liquid Metal Solders. *Nat. Electron.* **2024**, *7*, 598−609.
(235) Bock, D. C.; Marschilok, A. C.; Takeuchi, K. J.; Takeuchi, E. S. Batteries Used to Power Implantable Biomedical Devices. *Electrochim. Acta* **2012**, *84*, 155−164.
(236) Fan, F. R.; Tang, W.; Wang, Z. L. Flexible Nanogenerators for Energy Harvesting and Self-Powered Electronics. *Adv. Mater.* **2016**, *28*, 4283−4305.
(237) Yang, F.; Li, J.; Long, Y.; Zhang, Z.; Wang, L.; Sui, J.; Dong, Y.; Wang, Y.; Taylor, R.; Ni, D.; Cai, W.; Wang, P.; Hacker, T.; Wang, X. Wafer-Scale Heterostructured Piezoelectric Bio-Organic Thin Films. *Science* **2021**, *373*, 337−342.
(238) Andreu-Perez, J.; Poon, C. C.; Merrifield, R. D.; Wong, S. T.; Yang, G.-Z. Big Data for Health. *IEEE J. Biomed. Health Inform.* **2015**, *19*, 1193−1208.
(239) Yang, X.; Yi, J.; Wang, T.; Feng, Y.; Wang, J.; Yu, J.; Zhang, F.; Jiang, Z.; Lv, Z.; Li, H.; Huang, T.; Si, D.; Wang, X.; Cao, R.; Chen, X. Wet-Adhesive On-Skin Sensors based on Metal-Organic Frameworks for Wireless Monitoring of Metabolites in Sweat. *Adv. Mater.* **2022**, *34*, 2201768.
(240) Yi, J.; Ren, X.; Li, Y.; Yuan, Y.; Tang, W.; Wang, X.; Yu, J.; Yu, S.; Li, W.; Wang, J.; Loh, X. J.; Hu, B.; Chen, X. Rapid-Response Water-Shrink Films with High Output Work Density Based on Polyethylene Oxide and α-Cyclodextrin for Autonomous Wound Closure. *Adv. Mater.* **2024**, *36*, 2403551.
(241) Bakowies, D.; Thiel, W. Hybrid Models for Combined Quantum Mechanical and Molecular Mechanical Approaches. *J. Phys. Chem.* **1996**, *100*, 10580−10594.
(242) Hourahine, B.; Aradi, B.; Blum, V.; Bonafé, F.; Buccheri, A.; Camacho, C.; Cevallos, C.; Deshaye, M. Y.; Dumitrică, T.; Dominguez, A.; Ehlert, S.; Elstner, M.; van der Heide, T.; Hermann, J.; Irle, S.; Kranz, J. J.; Köhler, C.; Kowalczyk, T.; Kubař, T.; Lee, I. S.; et al. DFTB+, A Software Package for Efficient Approximate Density Functional Theory Based Atomistic Simulations. *J. Chem. Phys.* **2020**, *152*, 124101.
(243) Laio, A.; Parrinello, M. Escaping Free-Energy Minima. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 12562−12566.
(244) Izvekov, S.; Voth, G. A. A Multiscale Coarse-Graining Method for Biomolecular Systems. *J. Phys. Chem. B* **2005**, *109*, 2469−2473.
(245) Marrink, S. J.; Risselada, H. J.; Yefimov, S.; Tieleman, D. P.; de Vries, A. H. The MARTINI Force Field: Coarse Grained Model for Biomolecular Simulations. *J. Phys. Chem. B* **2007**, *111*, 7812−7824.
(246) Saunders, M. G.; Voth, G. A. Coarse-Graining Methods for Computational Biology. *Annual Review of Biophysics* **2013**, *42*, 73−93.
(247) Jin, J. H. Y.; Pak, A. J.; Durumeric, A. E. P.; Loose, T. D.; Voth, G. A. Bottom-Up Coarse-Graining: Principles and Perspectives. *J. Chem. Theory Comput.* **2022**, *18*, 5759.
(248) Thompson, A. P.; Aktulga, H. M.; Berger, R.; Bolintineanu, D. S.; Brown, W. M.; Crozier, P. S.; in't Veld, P. J.; Kohlmeyer, A.; Moore, S. G.; Nguyen, T. D.; Shan, R.; Stevens, M. J.; Tranchida, J.; Trott, C.; Plimpton, S. J. LAMMPS-A Flexible Simulation Tool for Particle-Based Materials Modeling at the Atomic, Meso, and Continuum Scales. *Comput. Phys. Commun.* **2022**, *271*, 108171.
(249) Marrink, S. J.; Monticelli, L.; Melo, M. N.; Alessandri, R.; Tieleman, D. P.; Souza, P. C. T. Two Decades of Martini: Better

Beads, Broader Scope. *Wiley Interdiscip. Rev. Comput. Mol. Sci.* **2023**, *13*, e1620.
(250) Noid, W. G. Perspective: Advances, Challenges, and Insight for Predictive Coarse-Grained Models. *J. Phys. Chem. B* **2023**, *127*, 4174−4207.
(251) Stevens, J. A.; Grünewald, F.; van Tilburg, P. A. M.; König, M.; Gilbert, B. R.; Brier, T. A.; Thornburg, Z. R.; Luthey-Schulten, Z.; Marrink, S. J. Molecular Dynamics Simulation of an Entire Cell. *Front. Chem.* **2023**, *11*, na DOI: 10.3389/fchem.2023.1106495.
(252) Keith, J. A.; Vassilev-Galindo, V.; Cheng, B.; Chmiela, S.; Gastegger, M.; Müller, K.-R.; Tkatchenko, A. Combining Machine Learning and Computational Chemistry for Predictive Insights Into Chemical Systems. *Chem. Rev.* **2021**, *121*, 9816−9872.
(253) Hermann, J.; Spencer, J.; Choo, K.; Mezzacapo, A.; Foulkes, W. M. C.; Pfau, D.; Carleo, G.; Noé, F. *ab initio* Quantum Chemistry with Neural-Network Wavefunctions. *Nat. Rev. Chem.* **2023**, *7*, 692−709.
(254) Ruggenthaler, M.; Sidler, D.; Rubio, A. Understanding Polaritonic Chemistry from *ab Initio* Quantum Electrodynamics. *Chem. Rev.* **2023**, *123*, 11191−11229.
(255) Taflove, A.; Brodwin, M. E. Numerical Solution of Steady-State Electromagnetic Scattering Problems Using the Time-Dependent Maxwell's Equations. *IEEE Trans. Microw. Theory Techn.* **1975**, *23*, 623−630.
(256) Jin, J.-M. *The Finite Element Method in Electromagnetics*; Wiley, 2014.
(257) Kimble, H. J. Strong Interactions of Single Atoms and Photons in Cavity QED. *Phys. Scr.* **1998**, *T76*, 127.
(258) Walther, H.; Varcoe, B. T. H.; Englert, B.-G.; Becker, T. Cavity Quantum Electrodynamics. *Rep. Prog. Phys.* **2006**, *69*, 1325.
(259) Hoffmann, N. M.; Schäfer, C.; Säkkinen, N.; Rubio, A.; Appel, H.; Kelly, A. Benchmarking Semiclassical and Perturbative Methods for Real-Time Simulations of Cavity-Bound Emission and Interference. *J. Chem. Phys.* **2019**, *151*, 244113.
(260) Li, T. E.; Chen, H.-T.; Subotnik, J. E. Comparison of Different Classical, Semiclassical, and Quantum Treatments of Light-Matter Interactions: Understanding Energy Conservation. *J. Chem. Theory Comput.* **2019**, *15*, 1957−1973.
(261) Hoffmann, N. M.; Schäfer, C.; Rubio, A.; Kelly, A.; Appel, H. Capturing Vacuum Fluctuations and Photon Correlations in Cavity Quantum Electrodynamics with Multitrajectory Ehrenfest Dynamics. *Phys. Rev. A* **2019**, *99*, 063819.
(262) Li, T. E.; Chen, H.-T.; Nitzan, A.; Subotnik, J. E. Quasiclassical Modeling of Cavity Quantum Electrodynamics. *Phys. Rev. A* **2020**, *101*, 033831.
(263) Unke, O. T.; Chmiela, S.; Sauceda, H. E.; Gastegger, M.; Poltavsky, I.; Schütt, K. T.; Tkatchenko, A.; Müller, K.-R. Machine Learning Force Fields. *Chem. Rev.* **2021**, *121*, 10142−10186.
(264) Meuwly, M. Machine Learning for Chemical Reactions. *Chem. Rev.* **2021**, *121*, 10218−10239.
(265) Bissell, R. A.; Córdova, E.; Kaifer, A. E.; Stoddart, J. F. A Chemically and Electrochemically Switchable Molecular Shuttle. *Nature* **1994**, *369*, 133−137.
(266) Li, C.; Lau, G. C.; Yuan, H.; Aggarwal, A.; Dominguez, V. L.; Liu, S.; Sai, H.; Palmer, L. C.; Sather, N. A.; Pearson, T. J.; Freedman, D. E.; Amiri, P. K.; de la Cruz, M. O.; Stupp, S. I. Fast and Programmable Locomotion of Hydrogel-Metal Hybrids Under Light and Magnetic Fields. *Sci. Robot.* **2020**, *5*, eabb9822.
(267) Yu, J.-C.; Browne, R. A.; Seo, S. E. Mechanically Robust, Self-Healing Polymer Nanocomposites with Tailorable Nanoparticle-Based Bonds. *Macromolecules* **2024**, *57*, 9059−9066.
(268) Myakonkaya, O.; Guibert, C.; Eastoe, J.; Grillo, I. Recovery of Nanoparticles Made Easy. *Langmuir* **2010**, *26*, 3794−3797.
(269) Grassian, V. H.; Haes, A. J.; Mudunkotuwa, I. A.; Demokritou, P.; Kane, A. B.; Murphy, C. J.; Hutchison, J. E.; Isaacs, J. A.; Jun, Y.-S.; Karn, B.; Khondaker, S. I.; Larsen, S. C.; Lau, B. L. T.; Pettibone, J. M.; Sadik, O. A.; Saleh, N. B.; Teague, C. NanoEHS - Defining Fundamental Science Needs: No Easy Feat When the Simple Itself is Complex. *Environ. Sci. Nano* **2016**, *3*, 15−27.
(270) Pati, P.; McGinnis, S.; Vikesland, P. J. Waste Not Want Not: Life Cycle Implications of Gold Recovery and Recycling from Nanowaste. *Environ. Sci. Nano* **2016**, *3*, 1133−1143.
(271) Salafi, T.; Zeming, K. K.; Zhang, Y. Advancements in Microfluidics for Nanoparticle Separation. *Lab Chip* **2017**, *17*, 11−33.
(272) Mondal, M. S.; Paul, A.; Rhaman, M. Recycling of Silver Nanoparticles from Electronic Waste *via* green Synthesis and Application of AgNPs-Chitosan Based Nanocomposite on Textile Material. *Sci. Rep.* **2023**, *13*, 13798.
(273) Neuhoff, M. J.; Wang, Y.; Vantangoli, N. J.; Poirier, M. G.; Castro, C. E.; Pfeifer, W. G. Recycling Materials for Sustainable DNA Origami Manufacturing. *Nano Lett.* **2024**, *24*, 12080−12087.
(274) Reijnders, L. Recycling of Non-Product Outputs Containing Rare Elements Originating in Nanomaterial Syntheses. *Environ. Sci. Nano* **2024**, *11*, 684−687.
(275) Andrew, L. J.; Lizundia, E.; MacLachlan, M. J. Designing for Degradation: Transient Devices Enabled by (Nano)Cellulose. *Adv. Mater.* **2025**, *37*, 2401560.
(276) Liu, Z.; Frasconi, M.; Lei, J.; Brown, Z. J.; Zhu, Z.; Cao, D.; Iehl, J.; Liu, G.; Fahrenbach, A. C.; Botros, Y. Y.; Farha, O. K.; Hupp, J. T.; Mirkin, C. A.; Fraser Stoddart, J. Selective Isolation of Gold Facilitated by Second-Sphere Coordination with α-Cyclodextrin. *Nat. Commun.* **2013**, *4*, 1855.
(277) Moghimi, S. M.; Hunter, A. C.; Murray, J. C. Nanomedicine: Current Status and Future Prospects. *FASEB J.* **2005**, *19*, 311−330.
(278) Patra, J. K.; Das, G.; Fraceto, L. F.; Campos, E. V. R.; Rodriguez-Torres, M. d. P.; Acosta-Torres, L. S.; Diaz-Torres, L. A.; Grillo, R.; Swamy, M. K.; Sharma, S.; Habtemariam, S.; Shin, H.-S. Nano Based Drug Delivery Systems: Recent Developments and Future Prospects. *J. Nanobiotechnology* **2018**, *16*, 71.
(279) Kyriakides, T. R; Raj, A.; Tseng, T. H; Xiao, H.; Nguyen, R.; Mohammed, F. S; Halder, S.; Xu, M.; Wu, M. J; Bao, S.; Sheu, W. C Biocompatibility of Nanomaterials and their Immunological Properties. *Biomed. Mater.* **2021**, *16*, 042005.
(280) Cabral, H.; Li, J.; Miyata, K.; Kataoka, K. Controlling the Biodistribution and Clearance of Nanomedicines. *Nat. Rev. Bioeng.* **2024**, *2*, 214−232.
(281) Wolfram, J.; Zhu, M.; Yang, Y.; Shen, J.; Gentile, E.; Paolino, D.; Fresta, M.; Nie, G.; Chen, C.; Shen, H.; Ferrari, M.; Zhao, Y. Safety of Nanoparticles in Medicine. *Curr. Drug Targets* **2015**, *16*, 1671−1681.
(282) Moss, D. M.; Siccardi, M. Optimizing Nanomedicine Pharmacokinetics Using Physiologically Based Pharmacokinetics Modeling. *Br. J. Pharmacol.* **2014**, *171*, 3963−3979.
(283) Cui, X.; Wang, X.; Chang, X.; Bao, L.; Wu, J.; Tan, Z.; Chen, J.; Li, J.; Gao, X.; Ke, Pu C.; Chen, C. A New Capacity of Gut Microbiota: Fermentation of Engineered Inorganic Carbon Nanomaterials into Endogenous Organic Metabolites. *Proc. Natl. Acad. Sci. U.S.A.* **2023**, *120*, e2218739120.
(284) Rosi, N. L.; Giljohann, D. A.; Thaxton, C. S.; Lytton-Jean, A. K. R.; Han, M. S.; Mirkin, C. A. Oligonucleotide-Modified Gold Nanoparticles for Intracellular Gene Regulation. *Science* **2006**, *312*, 1027−1030.
(285) Yang, L.; Zhang, X.; Ye, M.; Jiang, J.; Yang, R.; Fu, T.; Chen, Y.; Wang, K.; Liu, C.; Tan, W. Aptamer-Conjugated Nanomaterials and their Applications. *Adv. Drug. Delivery Rev.* **2011**, *63*, 1361−1370.
(286) Su, H.; Koo, J. M.; Cui, H. One-Component Nanomedicine. *J. Contr. Release* **2015**, *219*, 383−395.
(287) Tan, X.; Li, B. B.; Lu, X.; Jia, F.; Santori, C.; Menon, P.; Li, H.; Zhang, B.; Zhao, J. J.; Zhang, K. Light-Triggered, Self-Immolative Nucleic Acid-Drug Nanostructures. *J. Am. Chem. Soc.* **2015**, *137*, 6112−6115.
(288) Qian, E. A.; Wixtrom, A. I.; Axtell, J. C.; Saebi, A.; Jung, D.; Rehak, P.; Han, Y.; Moully, E. H.; Mosallaei, D.; Chow, S.; Messina, M. S.; Wang, J. Y.; Royappa, A. T.; Rheingold, A. L.; Maynard, H. D.; Král, P.; Spokoyny, A. M. Atomically Precise Organomimetic Cluster Nanomolecules Assembled *via* Perfluoroaryl-Thiol SNAr Chemistry. *Nat. Chem.* **2017**, *9*, 333−340.

(289) Li, H.; Zhang, B.; Lu, X.; Tan, X.; Jia, F.; Xiao, Y.; Cheng, Z.; Li, Y.; Silva, D. O.; Schrekker, H. S.; Zhang, K.; Mirkin, C. A. Molecular Spherical Nucleic Acids. *Proc. Natl. Acad. Sci. U.S.A.* **2018**, *115*, 4340−4344.
(290) Ebrahimi, S. B.; Samanta, D.; Mirkin, C. A. DNA-Based Nanostructures for Live-Cell Analysis. *J. Am. Chem. Soc.* **2020**, *142*, 11343−11356.
(291) Ferrer, J. R.; Sinegra, A. J.; Ivancic, D.; Yeap, X. Y.; Qiu, L.; Wang, J.-J.; Zhang, Z. J.; Wertheim, J. A.; Mirkin, C. A. Structure-Dependent Biodistribution of Liposomal Spherical Nucleic Acids. *ACS Nano* **2020**, *14*, 1682−1693.
(292) Keller, A.; Linko, V. Challenges and Perspectives of DNA Nanostructures in Biomedicine. *Angew. Chem. Int. Ed.* **2020**, *59*, 15818−15833.
(293) Distler, M. E.; Teplensky, M. H.; Bujold, K. E.; Kusmierz, C. D.; Evangelopoulos, M.; Mirkin, C. A. DNA Dendrons as Agents for Intracellular Delivery. *J. Am. Chem. Soc.* **2021**, *143*, 13513−13518.
(294) Divine, R.; Dang, H. V.; Ueda, G.; Fallas, J. A.; Vulovic, I.; Sheffler, W.; Saini, S.; Zhao, Y. T.; Raj, I. X.; Morawski, P. A.; Jennewein, M. F.; Homad, L. J.; Wan, Y.-H.; Tooley, M. R.; Seeger, F.; Etemadi, A.; Fahning, M. L.; Lazarovits, J.; Roederer, A.; Walls, A. C.; et al. Designed Proteins Assemble Antibodies into Modular Nanocages. *Science* **2021**, *372*, eabd9994.
(295) Teplensky, M. H.; Dittmar, J. W.; Qin, L.; Wang, S.; Evangelopoulos, M.; Zhang, B.; Mirkin, C. A. Spherical Nucleic Acid Vaccine Structure Markedly Influences Adaptive Immune Responses of Clinically Utilized Prostate Cancer Targets. *Adv. Healthc. Mater.* **2021**, *10*, e2101262.
(296) Winegar, P. H.; Figg, C. A.; Teplensky, M. H.; Ramani, N.; Mirkin, C. A. Modular Nucleic Acid Scaffolds for Synthesizing Monodisperse and Sequence-Encoded Antibody Oligomers. *Chem.* **2022**, *8*, 3018−3030.
(297) Fang, Y.; Cai, J.; Ren, M.; Zhong, T.; Wang, D.; Zhang, K. Inhalable Bottlebrush Polymer Bioconjugates as Vectors for Efficient Pulmonary Delivery of Oligonucleotides. *ACS Nano* **2024**, *18*, 592−599.
(298) Mahmoudi, M.; Landry, M. P.; Moore, A.; Coreas, R. The Protein Corona from Nanomedicine to Environmental Science. *Nat. Rev. Mater.* **2023**, *8*, 422−438.
(299) García-Álvarez, R.; Hadjidemetriou, M.; Sánchez-Iglesias, A.; Liz-Marzán, L. M.; Kostarelos, K. *in vivo* Formation of Protein Corona on Gold Nanoparticles. The Effect of their Size and Shape. *Nanoscale* **2018**, *10*, 1256−1264.
(300) Hajipour, M. J.; Safavi-Sohi, R.; Sharifi, S.; Mahmoud, N.; Ashkarran, A. A.; Voke, E.; Serpooshan, V.; Ramezankhani, M.; Milani, A. S.; Landry, M. P.; Mahmoudi, M. An Overview of Nanoparticle Protein Corona Literature. *Small* **2023**, *19*, 2301838.
(301) Ashkarran, A. A.; Gharibi, H.; Voke, E.; Landry, M. P.; Saei, A. A.; Mahmoudi, M. Measurements of Heterogeneity in Proteomics Analysis of the Nanoparticle Protein Corona across Core Facilities. *Nat. Commun.* **2022**, *13*, 6610.
(302) Cisneros, E. P.; Morse, B. A.; Savk, A.; Malik, K.; Peppas, N. A.; Lanier, O. L. The Role of Patient-Specific Variables in Protein Corona Formation and Therapeutic Efficacy in Nanomedicine. *J. Nanobiotechnology* **2024**, *22*, 714.
(303) Freund, R.; Lächelt, U.; Gruber, T.; Rühle, B.; Wuttke, S. Multifunctional Efficiency: Extending the Concept of Atom Economy to Functional Nanomaterials. *ACS Nano* **2018**, *12*, 2094−2105.
(304) Xu, Z.; Pan, F.; Sun, M.; Xu, J.; Munyaneza, N. E.; Croft, Z. L.; Cai, G.; Liu, G. Cascade Degradation and Upcycling of Polystyrene Waste to High-Value Chemicals. *Proc. Natl. Acad. Sci. U.S.A.* **2022**, *119*, e2203346119.
(305) Xu, Z.; Munyaneza, N. E.; Zhang, Q.; Sun, M.; Posada, C.; Venturo, P.; Rorrer, N. A.; Miscall, J.; Sumpter, B. G.; Liu, G. Chemical Upcycling of Polyethylene, Polypropylene, and Mixtures to High-Value Surfactants. *Science* **2023**, *381*, 666−671.
(306) Munyaneza, N. E.; Ji, R.; DiMarco, A.; Miscall, J.; Stanley, L.; Rorrer, N.; Qiao, R.; Liu, G. Chain-Length-Controllable Upcycling of Polyolefins to Sulfate Detergents. *Nat. Sustain.* **2024**, *7*, 1681−1690.
(307) Gallagher, M. J.; Allen, C.; Buchman, J. T.; Qiu, T. A.; Clement, P. L.; Krause, M. O. P.; Gilbertson, L. M. Research Highlights: Applications of Life-Cycle Assessment as a Tool for Characterizing Environmental Impacts of Engineered Nanomaterials. *Environ. Sci. Nano* **2017**, *4*, 276−281.
(308) Daly, C. A., Jr; Hernandez, R. Learning from the Machine: Uncovering Sustainable Nanoparticle Design Rules. *J. Phys. Chem. C* **2020**, *124*, 13409−13420.
(309) Thomas, B.; Raj, M. C.; B, A. K.; H, R. M.; Joy, J.; Moores, A.; Drisko, G. L.; Sanchez, C. Nanocellulose, a Versatile Green Platform: From Biosources to Materials and their Applications. *Chem. Rev.* **2018**, *118*, 11575−11625.
(310) Wang, Z. H.; Shen, D. K.; Wu, C. F.; Gu, S. State-of-the-Art on the Production and Application of Carbon Nanomaterials from Biomass. *Green Chem.* **2018**, *20*, 5031−5057.
(311) Wu, D.; Zhou, J.; Creyer, M. N.; Yim, W.; Chen, Z.; Messersmith, P. B.; Jokerst, J. V. Phenolic-Enabled Nanotechnology: Versatile Particle Engineering for Biomedicine. *Chem. Soc. Rev.* **2021**, *50*, 4432−4483.
(312) Wang, Q.; Zhou, R.; Sun, J.; Liu, J.; Zhu, Q. Naturally Derived Janus Cellulose Nanomaterials: Anisotropic Cellulose Nanomaterial Building Blocks and their Assembly into Asymmetric Structures. *ACS Nano* **2022**, *16*, 13468−13491.
(313) Ramos, N. C.; Manye Ibanez, M.; Mittal, R.; Janik, M. J.; Holewinski, A. Combining Renewable Electricity and Renewable Carbon: Understanding Reaction Mechanisms of Biomass-Derived Furanic Compounds for Design of Catalytic Nanomaterials. *Acc. Chem. Res.* **2023**, *56*, 2631−2641.
(314) Chandna, S.; Olivares M., C. A.; Baranovskii, E.; Engelmann, G.; Boker, A.; Tzschucke, C. C.; Haag, R. Lignin Upconversion by Functionalization and Network Formation. *Angew. Chem. Int. Ed.* **2024**, *63*, e202313945.
(315) Cao, S.; Rathi, P.; Wu, X.; Ghim, D.; Jun, Y.-S.; Singamaneni, S. Cellulose Nanomaterials in Interfacial Evaporators for Desalination: A "Natural" Choice. *Adv. Mater.* **2021**, *33*, 2000922.
(316) Figueiredo, P.; Lintinen, K.; Hirvonen, J. T.; Kostiainen, M. A.; Santos, H. A. Properties and Chemical Modifications of Lignin: Towards Lignin-Based Nanomaterials for Biomedical Applications. *Prog. Mater. Sci.* **2018**, *93*, 233−269.
(317) Chen, C. J.; Lin, M.; Wahl, C.; Li, Y. W.; Zhou, W. J.; Wang, Z.; Zhang, Y.; Mirkin, C. A. Dynamic Metal-Phenolic Coordination Complexes for Versatile Surface Nanopatterning. *J. Am. Chem. Soc.* **2023**, *145*, 7974−7982.
(318) Kramer, R. M.; Li, C.; Carter, D. C.; Stone, M. O.; Naik, R. R. Engineered Protein Cages for Nanomaterial Synthesis. *J. Am. Chem. Soc.* **2004**, *126*, 13282−13286.
(319) Chen, C. J.; Ng, D. Y. W.; Weil, T. Polymer Bioconjugates: Modern Design Concepts toward Precision Hybrid Materials. *Prog. Polym. Sci.* **2020**, *105*, 101241.
(320) Chen, C.; Wunderlich, K.; Mukherji, D.; Koynov, K.; Heck, A. J.; Raabe, M.; Barz, M.; Fytas, G.; Kremer, K.; Ng, D. Y. W.; Weil, T. Precision Anisotropic Brush Polymers by Sequence Controlled Chemistry. *J. Am. Chem. Soc.* **2020**, *142*, 1332−1340.
(321) Han, Z.; Guo, A. X.; Luo, T.; Cai, T.; Mirkin, C. A. Biomineralization of Semiconductor Quantum Dots using DNA-Functionalized Protein Nanoreactors. *Sci. Adv.* **2025**, *11*, eadv6906.
(322) Głowniak, S.; Szczęśniak, B.; Choma, J.; Jaroniec, M. Advances in Microwave Synthesis of Nanoporous Materials. *Adv. Mater.* **2021**, *33*, 2103477.
(323) Calvo, V.; González-Domínguez, J. M.; Benito, A. M.; Maser, W. K. Synthesis and Processing of Nanomaterials Mediated by Living Organisms. *Angew. Chem. Int. Ed.* **2022**, *61*, e202113286.
(324) Jeevanandam, J.; Kiew, S. F.; Boakye-Ansah, S.; Lau, S. Y.; Barhoum, A.; Danquah, M. K.; Rodrigues, J. Green Approaches for the Synthesis of Metal and Metal Oxide Nanoparticles using Microbial and Plant Extracts. *Nanoscale* **2022**, *14*, 2534−2571.
(325) Subbotina, E.; Ram, F.; Dvinskikh, S. V.; Berglund, L. A.; Olsén, P. Aqueous Synthesis of Highly Functional, Hydrophobic, and

Chemically Recyclable Cellulose Nanomaterials through Oxime Ligation. *Nat. Commun.* **2022**, *13*, 6924.
(326) Chen, C. J.; Xie, Z.; Wei, X. L.; Zheng, Z. J. Arbitrary and Parallel Nanofabrication of 3D Metal Structures with Polymer Brush Resists. *Small* **2015**, *11*, 6013−6017.
(327) Plata, D. L.; Janković, N. Z. Achieving Sustainable Nanomaterial Design though Strategic Cultivation of Big Data. *Nat. Nanotechnol.* **2021**, *16*, 612−614.
(328) Zhao, H.; Chen, W.; Huang, H.; Sun, Z.; Chen, Z.; Wu, L.; Zhang, B.; Lai, F.; Wang, Z.; Adam, M. L.; Pang, C. H.; Chu, P. K.; Lu, Y.; Wu, T.; Jiang, J.; Yin, Z.; Yu, X.-F. A Robotic Platform for the Synthesis of Colloidal Nanocrystals. *Nat. Synth.* **2023**, *2*, 505−514.
(329) Kuznetsova, V.; Coogan, Á.; Botov, D.; Gromova, Y.; Ushakova, E. V.; Gun'ko, Y. K. Expanding the Horizons of Machine Learning in Nanomaterials to Chiral Nanostructures. *Adv. Mater.* **2024**, *36*, 2308912.
(330) Macfarlane, R. J.; Lee, B.; Jones, M. R.; Harris, N.; Schatz, G. C.; Mirkin, C. A. Nanoparticle Superlattice Engineering with DNA. *Science* **2011**, *334*, 204−208.
(331) Samanta, D.; Zhou, W.; Ebrahimi, S. B.; Petrosko, S. H.; Mirkin, C. A. Programmable Matter: The Nanoparticle Atom and DNA Bond. *Adv. Mater.* **2022**, *34*, 2107875.
(332) Beaucage, S. L.; Caruthers, M. H. Deoxynucleoside Phosphoramidites—A New Class of Key Intermediates for Deoxypolynucleotide Synthesis. *Tetrahedron Lett.* **1981**, *22*, 1859−1862.
(333) Bollum, F. J. Oligodeoxyribonucleotide-Primed Reactions Catalyzed by Calf Thymus Polymerase. *J. Biol. Chem.* **1962**, *237*, 1945−1949.
(334) Palluk, S.; Arlow, D. H.; de Rond, T.; Barthel, S.; Kang, J. S.; Bector, R.; Baghdassarian, H. M.; Truong, A. N.; Kim, P. W.; Singh, A. K.; Hillson, N. J.; Keasling, J. D. *de novo* DNA Synthesis Using Polymerase-Nucleotide Conjugates. *Nat. Biotechnol.* **2018**, *36*, 645−650.
(335) Eisenstein, M. Enzymatic DNA Synthesis Enters New Phase. *Nat. Biotechnol.* **2020**, *38*, 1113−1115.
(336) Hoose, A.; Vellacott, R.; Storch, M.; Freemont, P. S.; Ryadnov, M. G. DNA Synthesis Technologies to Close the Gene Writing Gap. *Nat. Rev. Chem.* **2023**, *7*, 144−161.
(337) Thorpe, J. D.; O'Reilly, D.; Friščić, T.; Damha, M. J. Mechanochemical Synthesis of Short DNA Fragments. *Chem.—Eur. J.* **2020**, *26*, 8857−8861.
(338) Sandahl, A. F.; Nguyen, T. J. D.; Hansen, R. A.; Johansen, M. B.; Skrydstrup, T.; Gothelf, K. V. On-Demand Synthesis of Phosphoramidites. *Nat. Commun.* **2021**, *12*, 2760.
(339) Ferrazzano, L.; Corbisiero, D.; Tolomelli, A.; Cabri, W. From Green Innovations in Oligopeptide to Oligonucleotide Sustainable Synthesis: Differences and Synergies in TIDES Chemistry. *Green Chem.* **2023**, *25*, 1217−1236.
(340) Knouse, K. W.; deGruyter, J. N.; Schmidt, M. A.; Zheng, B.; Vantourout, J. C.; Kingston, C.; Mercer, S. E.; Mcdonald, I. M.; Olson, R. E.; Zhu, Y.; Hang, C.; Zhu, J.; Yuan, C.; Wang, Q.; Park, P.; Eastgate, M. D.; Baran, P. S. Unlocking P(V): Reagents for Chiral Phosphorothioate Synthesis. *Science* **2018**, *361*, 1234−1238.
(341) Huang, Y.; Knouse, K. W.; Qiu, S.; Hao, W.; Padial, N. M.; Vantourout, J. C.; Zheng, B.; Mercer, S. E.; Lopez-Ogalla, J.; Narayan, R.; Olson, R. E.; Blackmond, D. G.; Eastgate, M. D.; Schmidt, M. A.; McDonald, I. M.; Baran, P. S. A P(V) Platform for Oligonucleotide Synthesis. *Science* **2021**, *373*, 1265−1270.
(342) Knouse, K. W.; Flood, D. T.; Vantourout, J. C.; Schmidt, M. A.; McDonald, I. M.; Eastgate, M. D.; Baran, P. S. Nature Chose Phosphates and Chemists Should Too: How Emerging P(V) Methods Can Augment Existing Strategies. *ACS Cent. Sci.* **2021**, *7*, 1473−1485.
(343) Jain, M. L.; Bruice, P. Y.; Szabó, I. E.; Bruice, T. C. Incorporation of Positively Charged Linkages into DNA and RNA Backbones: A Novel Strategy for Antigene and Antisense Agents. *Chem. Rev.* **2012**, *112*, 1284−1309.
(344) Skakuj, K.; Bujold, K. E.; Mirkin, C. A. Mercury-Free Automated Synthesis of Guanidinium Backbone Oligonucleotides. *J. Am. Chem. Soc.* **2019**, *141*, 20171−20176.
(345) *Handbook of X-Ray Imaging*; CRC Press, 2017. DOI: 10.1201/9781351228251.
(346) *Applied Scanning Probe Methods IX*; Springer Berlin, Heidelberg, 2008. DOI: 10.1007/978-3-540-74083-4.
(347) Suzuki, Y.; Cardone, G.; Restrepo, D.; Zavattieri, P. D.; Baker, T. S.; Tezcan, F. A. Self-Assembly of Coherently Dynamic, Auxetic, Two-Dimensional Protein Crystals. *Nature* **2016**, *533*, 369−373.
(348) Chang, H.; Gnanasekaran, K.; Gianneschi, N. C.; Geiger, F. M. Bacterial Model Membranes Deform (resp. Persist) upon Ni^{2+} Binding to Inner Core (resp. O-Antigen) of Lipopolysaccharides. *J. Phys. Chem. B* **2019**, *123*, 4258−4270.
(349) Yao, L.; Ou, Z.; Luo, B.; Xu, C.; Chen, Q. Machine Learning to Reveal Nanoparticle Dynamics from Liquid-Phase TEM Videos. *ACS Cent. Sci.* **2020**, *6*, 1421−1430.
(350) Korpanty, J.; Gianneschi, N. C. Exploration of Organic Nanomaterials with Liquid-Phase Transmission Electron Microscopy. *Acc. Chem. Res.* **2023**, *56*, 2298−2312.
(351) Liu, Y.; Koo, K.; Mao, Z.; Fu, X.; Hu, X.; Dravid, V. P. Unraveling the Adsorption-Limited Hydrogen Oxidation Reaction at Palladium Surface *via in situ* Electron Microscopy. *Proc. Natl. Acad. Sci. U.S.A.* **2024**, *121*, e2408277121.
(352) Gnanasekaran, K.; Chang, H.; Smeets, P. J. M.; Korpanty, J.; Geiger, F. M.; Gianneschi, N. C. *in situ* Ni^{2+} Stain for Liposome Imaging by Liquid-Cell Transmission Electron Microscopy. *Nano Lett.* **2020**, *20*, 4292−4297.
(353) Koo, K.; Li, Z.; Liu, Y.; Ribet, S. M.; Fu, X.; Jia, Y.; Chen, X.; Shekhawat, G.; Smeets, P. J. M.; dos Reis, R.; Park, J.; Yuk, J. M.; Hu, X.; Dravid, V. P. Ultrathin Silicon Nitride Microchip for *In Situ/Operando* Microscopy with High Spatial Resolution and Spectral Visibility. *Sci. Adv.* **2024**, *10*, eadj6417.
(354) Park, J.; Zheng, H.; Lee, W. C.; Geissler, P. L.; Rabani, E.; Alivisatos, A. P. Direct Observation of Nanoparticle Superlattice Formation by Using Liquid Cell Transmission Electron Microscopy. *ACS Nano* **2012**, *6*, 2078−2085.
(355) Fu, X.; Wang, X.-D.; Zhao, B.; Zhang, Q.; Sun, S.; Wang, J.-J.; Zhang, W.; Gu, L.; Zhang, Y.; Zhang, W.-Z.; Wen, W.; Zhang, Z.; Chen, L.-q.; Yu, Q.; Ma, E. Atomic-Scale Observation of Non-Classical Nucleation-Mediated Phase Transformation in a Titanium Alloy. *Nat. Mater.* **2022**, *21*, 290−296.
(356) Deng, H. D.; Zhao, H.; Jin, N.; Hughes, L.; Savitzky, B. H.; Ophus, C.; Fraggedakis, D.; Borbély, A.; Yu, Y.-S.; Lomeli, E. G.; Yan, R.; Liu, J.; Shapiro, D. A.; Cai, W.; Bazant, M. Z.; Minor, A. M.; Chueh, W. C. Correlative Image Learning of Chemo-Mechanics in Phase-Transforming Solids. *Nat. Mater.* **2022**, *21*, 547−554.
(357) Yang, X.; Yang, Y.; Zhang, Z.; Li, M. Deep Learning Image Recognition-Assisted Atomic Force Microscopy for Single-Cell Efficient Mechanics in Co-Culture Environments. *Langmuir* **2024**, *40*, 837−852.
(358) Langer, R.; Peppas, N. A. Advances in Biomaterials, Drug Delivery, and Bionanotechnology. *AIChE J.* **2003**, *49*, 2990−3006.
(359) Baran, S. W.; Brown, P. C.; Baudy, A. R.; Fitzpatrick, S. C.; Frantz, C.; Fullerton, A.; Gan, J.; Hardwick, R. N.; Hillgren, K. M.; Kopec, A. K.; Liras, J. L.; Mendrick, D. L.; Nagao, R.; Proctor, W. R.; Ramsden, D.; Ribeiro, A. J. S.; Stresser, D.; Sung, K. E.; Sura, R.; Tetsuka, K.; et al. Perspectives on the Evaluation and Adoption of Complex *in vitro* Models in Drug Development: Workshop with the FDA and the Pharmaceutical Industry (IQ MPS Affiliate). *ALTEX* **2022**, *39*, 297−314.
(360) Ingber, D. E. Human Organs-on-Chips for Disease Modeling, Drug Development and Personalized Medicine. *Nat. Rev. Genet.* **2022**, *23*, 467−491.
(361) Mahapatra, C.; Lee, R.; Paul, M. K. Emerging Role and Promise of Nanomaterials in Organoid Research. *Drug Discovery Today* **2022**, *27*, 890−899.
(362) Shen, C.; Zhang, Z. J.; Li, X. X.; Huang, Y. P.; Wang, Y. X.; Zhou, H.; Xiong, L.; Wen, Y.; Zou, H.; Liu, Z. T. Intersection of Nanomaterials and Organoids Technology in Biomedicine. *Front. Immunol.* **2023**, *14*, 1172262.

(363) Discher, D. E.; Mooney, D. J.; Zandstra, P. W. Growth Factors, Matrices, and Forces Combine and Control Stem Cells. *Science* **2009**, *324*, 1673−1677.
(364) Bhardwaj, N.; Kundu, S. C. Electrospinning: A Fascinating Fiber Fabrication Technique. *Biotechnol. Adv.* **2010**, *28*, 325−347.
(365) Jiang, Y.; Krishnan, N.; Heo, J.; Fang, R. H.; Zhang, L. Nanoparticle-Hydrogel Superstructures for Biomedical Applications. *J. Contr. Release* **2020**, *324*, 505−521.
(366) Kim, J.; Koo, B. K.; Knoblich, J. A. Human Organoids: Model Systems for Human Biology and Medicine. *Nat. Rev. Mol. Cell Biol.* **2020**, *21*, 571−584.
(367) Heo, J. H.; Kang, D.; Seo, S. J.; Jin, Y. Engineering the Extracellular Matrix for Organoid Culture. *Int. J. Stem Cells* **2022**, *15*, 60−69.
(368) Abdel Fattah, A. R.; Kolaitis, N.; Van Daele, K.; Daza, B.; Rustandi, A. G.; Ranga, A. Targeted Mechanical Stimulation *via* Magnetic Nanoparticles Guides *in vitro* Tissue Development. *Nat. Commun.* **2023**, *14*, 5281.
(369) Gan, Z.; Qin, X.; Liu, H.; Liu, J.; Qin, J. Recent Advances in Defined Hydrogels in Organoid Research. *Bioact. Mater.* **2023**, *28*, 386−401.
(370) Murphy, S. V.; Atala, A. 3D Bioprinting of Tissues and Organs. *Nat. Biotechnol.* **2014**, *32*, 773−785.
(371) Nauryzgaliyeva, Z.; Goux Corredera, I.; Garreta, E.; Montserrat, N. Harnessing Mechanobiology for Kidney Organoid Research. *Front. Cell Dev. Biol.* **2023**, *11*, 1273923.
(372) García-Astrain, C.; Henriksen-Lacey, M.; Lenzi, E.; Renero-Lecuna, C.; Langer, J.; Piñeiro, P.; Molina-Martínez, B.; Plou, J.; Jimenez de Aberasturi, D.; Liz-Marzán, L. M. A Scaffold-Assisted 3D Cancer Cell Model for Surface-Enhanced Raman Scattering-Based Real-Time Sensing and Imaging. *ACS Nano* **2024**, *18*, 11257−11269.
(373) Vázquez-Aristizabal, P.; Henriksen-Lacey, M.; García-Astrain, C.; Jimenez de Aberasturi, D.; Langer, J.; Epelde, C.; Litti, L.; Liz-Marzán, L. M.; Izeta, A. Biofabrication and Monitoring of a 3D Printed Skin Model for Melanoma. *Adv. Healthc. Mater.* **2024**, *13*, 2401136.
(374) Zhang, S.; Grifno, G.; Passaro, R.; Regan, K.; Zheng, S.; Hadzipasic, M.; Banerji, R.; O'Connor, L.; Chu, V.; Kim, S. Y.; Yang, J.; Shi, L.; Karrobi, K.; Roblyer, D.; Grinstaff, M. W.; Nia, H. T. Intravital Measurements of Solid Stresses in Tumours Reveal Length-Scale and Microenvironmentally Dependent Force Transmission. *Nat. Biomed. Eng.* **2023**, *7*, 1473−1492.
(375) Suhito, I. R.; Kim, J. W.; Koo, K. M.; Nam, S. A.; Kim, Y. K.; Kim, T. H. *in situ* Detection of Kidney Organoid Generation from Stem Cells using a Simple Electrochemical Method. *Adv. Sci.* **2022**, *9*, e2200074.
(376) Liu, G.; Wei, J.; Li, X.; Tian, M.; Wang, Z.; Shen, C.; Sun, W.; Li, C.; Li, X.; Lv, E.; Tian, S.; Wang, J.; Xu, S.; Zhao, B. Near-Infrared-Responded High Sensitivity Nanoprobe for Steady and Visualized Detection of Albumin in Hepatic Organoids and Mouse Liver. *Adv. Sci.* **2022**, *9*, e2202505.
(377) Goyal, G.; Prabhala, P.; Mahajan, G.; Bausk, B.; Gilboa, T.; Xie, L.; Zhai, Y.; Lazarovits, R.; Mansour, A.; Kim, M. S.; Patil, A.; Curran, D.; Long, J. M.; Sharma, S.; Junaid, A.; Cohen, L.; Ferrante, T. C.; Levy, O.; Prantil-Baun, R.; Walt, D. R.; et al. Ectopic Lymphoid Follicle Formation and Human Seasonal Influenza Vaccination Responses Recapitulated in an Organ-on-a-Chip. *Adv. Sci.* **2022**, *9*, e2103241.
(378) Deng, Y.; Li, L.; Xu, J.; Yao, Y.; Ding, J.; Wang, L.; Luo, C.; Yang, W.; Li, L. A Biomimetic Human Disease Model of Bacterial Keratitis Using a Cornea-on-a-Chip System. *Biomater. Sci.* **2024**, *12*, 5239−5252.
(379) Herland, A.; Maoz, B. M.; Das, D.; Somayaji, M. R.; Prantil-Baun, R.; Novak, R.; Cronce, M.; Huffstater, T.; Jeanty, S. S. F.; Ingram, M.; Chalkiadaki, A.; Benson Chou, D.; Marquez, S.; Delahanty, A.; Jalili-Firoozinezhad, S.; Milton, Y.; Sontheimer-Phelps, A.; Swenor, B.; Levy, O.; Parker, K. K.; et al. Quantitative Prediction of Human Pharmacokinetic Responses to Drugs *via* Fluidically Coupled Vascularized Organ Chips. *Nat. Biomed. Eng.* **2020**, *4*, 421−436.
(380) Novak, R.; Ingram, M.; Marquez, S.; Das, D.; Delahanty, A.; Herland, A.; Maoz, B. M.; Jeanty, S. S. F.; Somayaji, M. R.; Burt, M.; Calamari, E.; Chalkiadaki, A.; Cho, A.; Choe, Y.; Chou, D. B.; Cronce, M.; Dauth, S.; Divic, T.; Fernandez-Alcon, J.; Ferrante, T.; et al. Robotic Fluidic Coupling and Interrogation of Multiple Vascularized Organ Chips. *Nat. Biomed. Eng.* **2020**, *4*, 407−420.
(381) Blumenrath, S. H.; Lee, B. Y.; Low, L.; Prithviraj, R.; Tagle, D. Tackling Rare Diseases: Clinical Trials on Chips. *Exp. Biol. Med. (Maywood)* **2020**, *245*, 1155−1162.
(382) Singh, N.; Ali, M. A.; Rai, P.; Sharma, A.; Malhotra, B. D.; John, R. Microporous Nanocomposite Enabled Microfluidic Biochip for Cardiac Biomarker Detection. *ACS Appl. Mater. Interfaces* **2017**, *9*, 33576−33588.
(383) Nasr, B.; Chatterton, R.; Yong, J. H. M.; Jamshidi, P.; D'Abaco, G. M.; Bjorksten, A. R.; Kavehei, O.; Chana, G.; Dottori, M.; Skafidas, E. Self-Organized Nanostructure Modified Microelectrode for Sensitive Electrochemical Glutamate Detection in Stem Cells-Derived Brain Organoids. *Biosensors* **2018**, *8*, 14.
(384) Liu, S.; Kumari, S.; He, H.; Mishra, P.; Singh, B. N.; Singh, D.; Liu, S.; Srivastava, P.; Li, C. Biosensors Integrated 3D Organoid/Organ-on-a-Chip System: A Real-Time Biomechanical, Biophysical, and Biochemical Monitoring and Characterization. *Biosens. Bioelectron.* **2023**, *231*, 115285.
(385) Debruyne, A. C.; Okkelman, I. A.; Heymans, N.; Pinheiro, C.; Hendrix, A.; Nobis, M.; Borisov, S. M.; Dmitriev, R. I. Live Microscopy of Multicellular Spheroids with the Multimodal Near-Infrared Nanoparticles Reveals Differences in Oxygenation Gradients. *ACS Nano* **2024**, *18*, 12168−12186.
(386) Le Floch, P.; Li, Q.; Lin, Z.; Zhao, S.; Liu, R.; Tasnim, K.; Jiang, H.; Liu, J. Stretchable Mesh Nanoelectronics for 3D Single-Cell Chronic Electrophysiology from Developing Brain Organoids. *Adv. Mater.* **2022**, *34*, e2106829.
(387) Lin, Z.; Wang, W.; Liu, R.; Li, Q.; Lee, J.; Hirschler, C.; Liu, J. Cyborg Organoids Integrated with Stretchable Nanoelectronics Can Be Functionally Mapped During Development. *Nat. Protoc.* **2025**, DOI: 10.1038/s41596-025-01147-7.
(388) Sanchez-Lengeling, B.; Aspuru-Guzik, A. Inverse Molecular Design Using Machine Learning: Generative Models for Matter Engineering. *Science* **2018**, *361*, 360−365.
(389) Kim, B.; Lee, S.; Kim, J. Inverse Design of Porous Materials using Artificial Neural Networks. *Sci. Adv.* **2020**, *6*, eaax9324.
(390) Long, T.; Fortunato, N. M.; Opahle, I.; Zhang, Y.; Samathrakis, I.; Shen, C.; Gutfleisch, O.; Zhang, H. Constrained Crystals Deep Convolutional Generative Adversarial Network for the Inverse Design of Crystal Structures. *npj Comput. Mater.* **2021**, *7*, 66.
(391) Menon, D.; Ranganathan, R. A Generative Approach to Materials Discovery, Design, and Optimization. *ACS Omega* **2022**, *7*, 25958−25973.
(392) Pun, G. P. P.; Batra, R.; Ramprasad, R.; Mishin, Y. Physically Informed Artificial Neural Networks for Atomistic Modeling of Materials. *Nat. Commun.* **2019**, *10*, 2339.
(393) Lundberg, S. M.; Erion, G.; Chen, H.; DeGrave, A.; Prutkin, J. M.; Nair, B.; Katz, R.; Himmelfarb, J.; Bansal, N.; Lee, S.-I. From Local Explanations to Global Understanding with Explainable AI for Trees. *Nat. Mach. Intell.* **2020**, *2*, 56−67.
(394) Zhong, X.; Gallagher, B.; Liu, S.; Kailkhura, B.; Hiszpanski, A.; Han, T. Y.-J. Explainable Machine Learning in Materials Science. *npj Comput. Mater.* **2022**, *8*, 204.
(395) Schrier, J.; Norquist, A. J.; Buonassisi, T.; Brgoch, J. In Pursuit of the Exceptional: Research Directions for Machine Learning in Chemical and Materials Science. *J. Am. Chem. Soc.* **2023**, *145*, 21699−21716.
(396) Huang, B.; von Rudorff, G. F.; von Lilienfeld, O. A. The Central Role of Density Functional Theory in the AI Age. *Science* **2023**, *381*, 170−175.
(397) Szymanski, N. J.; Rendy, B.; Fei, Y.; Kumar, R. E.; He, T.; Milsted, D.; McDermott, M. J.; Gallant, M.; Cubuk, E. D.; Merchant,

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

A.; Kim, H.; Jain, A.; Bartel, C. J.; Persson, K.; Zeng, Y.; Ceder, G. An Autonomous Laboratory for the Accelerated Synthesis of Novel Materials. *Nature* **2023**, *624*, 86−91.

(398) O'Dell, Z. J.; Knobeloch, M.; Skrabalak, S. E.; Willets, K. A. High-Throughput All-Optical Determination of Nanorod Size and Orientation. *Nano Lett.* **2024**, *24*, 7269−7275.

(399) Tom, G.; Schmid, S. P.; Baird, S. G.; Cao, Y.; Darvish, K.; Hao, H.; Lo, S.; Pablo-García, S.; Rajaonson, E. M.; Skreta, M.; Yoshikawa, N.; Corapi, S.; Akkoc, G. D.; Strieth-Kalthoff, F.; Seifrid, M.; Aspuru-Guzik, A. Self-Driving Laboratories for Chemistry and Materials Science. *Chem. Rev.* **2024**, *124*, 9633−9732.

(400) Vernon, K. L.; Pungsrisai, T.; Wahab, O. J.; Alden, S. E.; Zhong, Y.; Choi, M.-H.; Verma, E.; Bentley, A. K.; Bailey, K. O.; Skrabalak, S. E.; Ye, X.; Willets, K. A.; Baker, L. A. Optically Transparent Carbon Electrodes for Single Entity Electrochemistry. *ACS Electrochem.* **2025**, *1*, 93.

(401) Jain, A.; Ong, S. P.; Hautier, G.; Chen, W.; Richards, W. D.; Dacek, S.; Cholia, S.; Gunter, D.; Skinner, D.; Ceder, G.; Persson, K. A. Commentary: The Materials Project: A Materials Genome Approach to Accelerating Materials Innovation. *APL Mater.* **2013**, *1*, 011002.

(402) Saal, J. E.; Kirklin, S.; Aykol, M.; Meredig, B.; Wolverton, C. Materials Design and Discovery with High-Throughput Density Functional Theory: The Open Quantum Materials Database (OQMD). *JOM* **2013**, *65*, 1501−1509.

(403) Jablonka, K. M.; Schwaller, P.; Ortega-Guerrero, A.; Smit, B. Leveraging Large Language Models for Predictive Chemistry. *Nat. Mach. Intell.* **2024**, *6*, 161−169.

(404) Attia, P. M.; Grover, A.; Jin, N.; Severson, K. A.; Markov, T. M.; Liao, Y.-H.; Chen, M. H.; Cheong, B.; Perkins, N.; Yang, Z.; Herring, P. K.; Aykol, M.; Harris, S. J.; Braatz, R. D.; Ermon, S.; Chueh, W. C. Closed-Loop Optimization of Fast-Charging Protocols for Batteries with Machine Learning. *Nature* **2020**, *578*, 397−402.

(405) Angello, N. H.; Friday, D. M.; Hwang, C.; Yi, S.; Cheng, A. H.; Torres-Flores, T. C.; Jira, E. R.; Wang, W.; Aspuru-Guzik, A.; Burke, M. D.; Schroeder, C. M.; Diao, Y.; Jackson, N. E. Closed-Loop Transfer Enables Artificial Intelligence to Yield Chemical Knowledge. *Nature* **2024**, *633*, 351−358.

(406) Strieth-Kalthoff, F.; Hao, H.; Rathore, V.; Derasp, J.; Gaudin, T.; Angello, N. H.; Seifrid, M.; Trushina, E.; Guy, M.; Liu, J.; Tang, X.; Mamada, M.; Wang, W.; Tsagaantsooj, T.; Lavigne, C.; Pollice, R.; Wu, T. C.; Hotta, K.; Bodo, L.; Li, S.; et al. Delocalized, Asynchronous, Closed-Loop Discovery of Organic Laser Emitters. *Science* **2024**, *384*, eadk9227.

(407) Sukharev, M.; Seideman, T. Phase and Polarization Control as a Route to Plasmonic Nanodevices. *Nano Lett.* **2006**, *6*, 715−719.

(408) Ashiq, F.; Asif, M.; Ahmad, M. B.; Zafar, S.; Masood, K.; Mahmood, T.; Mahmood, M. T.; Lee, I. H. CNN-Based Object Recognition and Tracking System to Assist Visually Impaired People. *IEEE Access* **2022**, *10*, 14819−14834.

(409) Bouguettaya, A.; Zarzour, H.; Taberkit, A. M.; Kechida, A. A Review on Early Wildfire Detection from Unmanned Aerial Vehicles using Deep Learning-Based Computer Vision Algorithms. *Signal Process.* **2022**, *190*, 108309.

(410) Xiao, Q.; Chang, X.; Zhang, X.; Liu, X. Multi-Information Spatial-Temporal LSTM Fusion Continuous Sign Language Neural Machine Translation. *IEEE Access* **2020**, *8*, 216718−216728.

(411) Liu, X.; Zheng, Y.; Du, Z.; Ding, M.; Qian, Y.; Yang, Z.; Tang, J. GPT Understands, Too. *AI Open* **2024**, *5*, 208.

(412) Yi, X.; Walia, E.; Babyn, P. Generative Adversarial Network in Medical Imaging: A Review. *Med. Image Anal.* **2019**, *58*, 101552.

(413) Zhang, X.; Guo, Y. OmiTrans: Generative Adversarial Networks Based Omics-to-Omics Translation Framework. In *2022 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)*, 6−8 Dec. 2022; pp 653−659. DOI: 10.1109/BIBM55620.2022.9995537.

(414) Hegarty, J.; dos Reis, R.; Dravid, V. P. Laundry to Laboratory: Automated Image Analysis for the Characterization of Fibrous Microplastics. *ACS ES&T Water* **2025**, *5*, 2848−2860.

(415) Ha, T.; Lee, D.; Kwon, Y.; Park, M. S.; Lee, S.; Jang, J.; Choi, B.; Jeon, H.; Kim, J.; Choi, H.; Seo, H.-T.; Choi, W.; Hong, W.; Park, Y. J.; Jang, J.; Cho, J.; Kim, B.; Kwon, H.; Kim, G.; Oh, W. S.; et al. AI-Driven Robotic Chemist for Autonomous Synthesis of Organic Molecules. *Sci. Adv.* **2023**, *9*, eadj0461.

(416) Abolhasani, M.; Kumacheva, E. The Rise of Self-Driving Labs in Chemical and Materials Sciences. *Nat. Synth* **2023**, *2*, 483−492.

(417) Boiko, D. A.; MacKnight, R.; Kline, B.; Gomes, G. Autonomous Chemical Research with Large Language Models. *Nature* **2023**, *624*, 570−578.

(418) Jiang, Y.; Salley, D.; Sharma, A.; Keenan, G.; Mullin, M.; Cronin, L. An Artificial Intelligence Enabled Chemical Synthesis Robot for Exploration and Optimization of Nanomaterials. *Sci. Adv.* **2022**, *8*, eabo2626.

(419) Arias, D. S.; Taylor, R. E. Scientific Discovery at the Press of a Button: Navigating Emerging Cloud Laboratory Technology. *Adv. Mater. Technologies* **2024**, *9*, 2400084.

(420) Volk, A. A.; Abolhasani, M. Performance Metrics to Unleash the Power of Self-Driving Labs in Chemistry and Materials Science. *Nat. Commun.* **2024**, *15*, 1378.

(421) Hammer, A. J. S.; Leonov, A. I.; Bell, N. L.; Cronin, L. Chemputation and the Standardization of Chemical Informatics. *JACS Au* **2021**, *1*, 1572−1587.

(422) Wang, Z.; Cruse, K.; Fei, Y.; Chia, A.; Zeng, Y.; Huo, H.; He, T.; Deng, B.; Kononova, O.; Ceder, G. ULSA: Unified Language of Synthesis Actions for the Representation of Inorganic Synthesis Protocols. *Digit. Discovery* **2022**, *1*, 313−324.

(423) Ozgulbas, D. Y.; Jensen, D.; Butler, R.; Vescovi, R.; Foster, I. T.; Irvin, M.; Nakaye, Y.; Chu, M.; Dufresne, E. M.; Seifert, S.; Babnigg, G.; Ramanathan, A.; Zhang, Q. Robotic Pendant Drop: Containerless Liquid for μs-Resolved, AI-Executable XPCS. *Light Sci. Appl.* **2023**, *12*, 196.

(424) Halwani, A. A. Development of Pharmaceutical Nanomedicines: From the Bench to the Market. *Pharmaceutics* **2022**, *14*, 106.

(425) Atkins, J. T.; George, G. C.; Hess, K.; Marcelo-Lewis, K. L.; Yuan, Y.; Borthakur, G.; Khozin, S.; LoRusso, P.; Hong, D. S. Pre-Clinical Animal Models are Poor Predictors of Human Toxicities in Phase 1 Oncology Clinical Trials. *Br. J. Cancer* **2020**, *123*, 1496−1501.

(426) Chiaradia, I.; Lancaster, M. A. Brain Organoids for the Study of Human Neurobiology at the Interface of *In Vitro* and *In Vivo*. *Nat. Neurosci.* **2020**, *23*, 1496−1508.

(427) Schutgens, F.; Clevers, H. Human Organoids: Tools for Understanding Biology and Treating Diseases. *Annu. Rev. Pathol.* **2020**, *15*, 211−234.

(428) Hofer, M.; Lutolf, M. P. Engineering Organoids. *Nat. Rev. Mater.* **2021**, *6*, 402−420.

(429) Kim, S. K.; Kim, Y. H.; Park, S.; Cho, S.-W. Organoid Engineering with Microfluidics and Biomaterials for Liver, Lung Disease, and Cancer Modeling. *Acta Biomaterialia* **2021**, *132*, 37−51.

(430) Gong, J.; Li, M.; Kang, J.; Yin, Z.; Cha, Z.; Yang, J.; Xu, H. Microfluidic Techniques for Next-Generation Organoid Systems. *Adv. Mater. Int.* **2022**, *9*, 2200846.

(431) Zhao, Z.; Chen, X.; Dowbaj, A. M.; Sljukic, A.; Bratlie, K.; Lin, L.; Fong, E. L. S.; Balachander, G. M.; Chen, Z.; Soragni, A.; Huch, M.; Zeng, Y. A.; Wang, Q.; Yu, H. Organoids. *Nat. Rev. Methods Primers* **2022**, *2*, 94.

(432) Liu, H.; Gan, Z.; Qin, X.; Wang, Y.; Qin, J. Advances in Microfluidic Technologies in Organoid Research. *Adv. Healthc. Mater.* **2024**, *13*, 2302686.

(433) Sun, C. P.; Lan, H. R.; Fang, X. L.; Yang, X. Y.; Jin, K. T. Organoid Models for Precision Cancer Immunotherapy. *Front. Immunol.* **2022**, *13*, 770465.

(434) Polak, R.; Zhang, E. T.; Kuo, C. J. Cancer Organoids 2.0: Modelling the Complexity of the Tumor Immune Microenvironment. *Nat. Rev. Cancer* **2024**, *24*, 523−539.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

(435) Guil-Luna, S.; Sedlik, C.; Piaggio, E. Humanized Mouse Models to Evaluate Cancer Immunotherapeutics. *Annu. Rev. Cancer Biol.* **2021**, *5*, 119−136.
(436) Chuprin, J.; Buettner, H.; Seedhom, M. O.; Greiner, D. L.; Keck, J. G.; Ishikawa, F.; Shultz, L. D.; Brehm, M. A. Humanized Mouse Models for Immuno-Oncology Research. *Nature Reviews Clinical Oncology* **2023**, *20*, 192−206.
(437) Chupp, D. P.; Rivera, C. E.; Zhou, Y.; Xu, Y.; Ramsey, P. S.; Xu, Z.; Zan, H.; Casali, P. A Humanized Mouse that Mounts Mature Class-Switched, Hypermutated and Neutralizing Antibody Responses. *Nat. Immunol.* **2024**, *25*, 1489−1506.
(438) Williams, S. T.; Wells, G.; Conroy, S.; Gagg, H.; Allen, R.; Rominiyi, O.; Helleday, T.; Hullock, K.; Pennington, C. E. W.; Rantala, J.; Collis, S. J.; Danson, S. J. Precision Oncology using *ex vivo* Technology: A Step Towards Individualised Cancer Care? *Expert Rev. Mol. Med.* **2022**, *24*, e39.
(439) Mitchell, M. J.; Billingsley, M. M.; Haley, R. M.; Wechsler, M. E.; Peppas, N. A.; Langer, R. Engineering Precision Nanoparticles for Drug Delivery. *Nat. Rev. Drug Discovery* **2021**, *20*, 101−124.
(440) Plou, J.; Valera, P. S.; García, I.; de Albuquerque, C. D. L.; Carracedo, A.; Liz-Marzán, L. M. Prospects of Surface-Enhanced Raman Spectroscopy for Biomarker Monitoring toward Precision Medicine. *ACS Photonics* **2022**, *9*, 333−350.
(441) Svensson, E.; von Mentzer, U.; Stubelius, A. Achieving Precision Healthcare through Nanomedicine and Enhanced Model Systems. *ACS Mater. Au* **2024**, *4*, 162−173.
(442) Singh, A. V.; Ansari, M. H. D.; Rosenkranz, D.; Maharjan, R. S.; Kriegel, F. L.; Gandhi, K.; Kanase, A.; Singh, R.; Laux, P.; Luch, A. Artificial Intelligence and Machine Learning in Computational Nanotoxicology: Unlocking and Empowering Nanomedicine. *Adv. Healthc. Mater.* **2020**, *9*, e1901862.
(443) Curion, F.; Theis, F. J. Machine Learning Integrative Approaches to Advance Computational Immunology. *Genome Med.* **2024**, *16*, 80.
(444) Usset, J.; Rosendahl Huber, A.; Andrianova, M. A.; Batlle, E.; Carles, J.; Cuppen, E.; Elez, E.; Felip, E.; Gómez-Rey, M.; Lo Giacco, D.; Martinez-Jimenez, F.; Muñoz-Couselo, E.; Siu, L. L.; Tabernero, J.; Vivancos, A.; Muiños, F.; Gonzalez-Perez, A.; Lopez-Bigas, N. Five Latent Factors Underlie Response to Immunotherapy. *Nat. Genet.* **2024**, *56*, 2112−2120.
(445) Vulpis, E.; Giulimondi, F.; Digiacomo, L.; Zingoni, A.; Safavi-Sohi, R.; Sharifi, S.; Caracciolo, G.; Mahmoudi, M. The Possible Role of Sex As an Important Factor in Development and Administration of Lipid Nanomedicine-Based COVID-19 Vaccine. *Mol. Pharmaceutics* **2021**, *18*, 2448−2453.
(446) Peppas, N. A.; Hilt, J. Z.; Thomas, J. B. *Nanotechnology in Therapeutics: Current Technology and Applications*; Horizon Bioscience, 2007.
(447) Mulvaney, P.; Parak, W. J.; Caruso, F.; Weiss, P. S. Standardizing Nanomaterials. *ACS Nano* **2016**, *10*, 9763−9764.
(448) Lammers, T.; Storm, G. Setting Standards to Promote Progress in Bio-Nano Science. *Nat. Nanotechnol.* **2019**, *14*, 626−626.
(449) Queipo, P.; Gonzalez, D.; Reinhardt, A.; Zadrozny, T.; Cioffi, M.; Bianchin, A.; Matteazzi, P. NANO, the Technology Integrating and Innovation Platform: Nanotechnologies-Essential Part of Sustainable Development. *SDFM* **2015**, 73−79.
(450) *A Quadrennial Review of the National Nanotechnology Initiative*, The National Academies Press, 2020. DOI: 10.17226/25729.
(451) Maier, D.; Exner, T. E.; Papadiamantis, A. G.; Ammar, A.; Tsoumanis, A.; Doganis, P.; Rouse, I.; Slater, L. T.; Gkoutos, G. V.; Jeliazkova, N.; Ilgenfritz, H.; Ziegler, M.; Gerhard, B.; Kopetsky, S.; Joshi, D.; Walker, L.; Svendsen, C.; Sarimveis, H.; Lobaskin, V.; Himly, M. Harmonising Knowledge for Safer Materials *via* the "NanoCommons" Knowledge Base. *Front. Phys.* **2023**, *11*, 1271842 DOI: 10.3389/fphy.2023.1271842.
(452) *caNanoLab*. https://cananolab.cancer.gov (accessed 2025 January 30).
(453) Crist, R. M.; Grossman, J. H.; Patri, A. K.; Stern, S. T.; Dobrovolskaia, M. A.; Adiseshaiah, P. P.; Clogston, J. D.; McNeil, S. E. Common Pitfalls in Nanotechnology: Lessons Learned from NCI's Nanotechnology Characterization Laboratory. *Integr. Biol. (Camb)* **2013**, *5*, 66−73.
(454) Dobrovolskaia, M. A. Lessons Learned from Immunological Characterization of Nanomaterials at the Nanotechnology Characterization Laboratory. *Front. Immunol.* **2022**, *13*, 984252.
(455) Harten, P.; Helgen, H.; Melendez, W.; Beach, B.; Boyes, W. K.; Sotiropoulos, I.; Karatzas, P.; Sarimveis, H.; Mortensen, H. M. Mining, Refining, and QSAR Analysing the Nanoinformatics in EPA NaKnowBase. *Environ. Sci. Nano* **2024**, *11*, 2262−2274.
(456) Amos, J. D.; Tian, Y.; Zhang, Z.; Lowry, G. V.; Wiesner, M. R.; Hendren, C. O. The NanoInformatics Knowledge Commons: Capturing Spatial and Temporal Nanomaterial Transformations in Diverse Systems. *Nanoimpact* **2021**, *23*, 100331.
(457) *Materials Project*. http://www.materialsgenome.org/. (accessed 2025 March 13).
(458) Gunter, D.; Cholia, S.; Jain, A.; Kocher, M.; Persson, K.; Ramakrishnan, L.; Ong, S. P.; Ceder, G.Community Accessible Datastore of High-Throughput Calculations: Experiences from the Materials Project. In *2012 SC Companion: High Performance Computing, Networking Storage and Analysis*, 10−16 Nov. 2012, pp 1244−1251.
(459) Qu, X.; Jain, A.; Rajput, N. N.; Cheng, L.; Zhang, Y.; Ong, S. P.; Brafman, M.; Maginn, E.; Curtiss, L. A.; Persson, K. A. The Electrolyte Genome Project: A Big Data Approach in Battery Materials Discovery. *Comput. Mater. Sci.* **2015**, *103*, 56−67.
(460) Editors. What is Nano? *Nat. Nanotechnol.* **2016**, *11*, 575−575.
(461) Jeliazkova, N.; Chomenidis, C.; Doganis, P.; Fadeel, B.; Grafström, R.; Hardy, B.; Hastings, J.; Hegi, M.; Jeliazkov, V.; Kochev, N.; Kohonen, P.; Munteanu, C. R.; Sarimveis, H.; Smeets, B.; Sopasakis, P.; Tsiliki, G.; Vorgrimmler, D.; Willighagen, E. The eNanoMapper Database for Nanomaterial Safety Information. *Beilstein J. Nanotechnol.* **2015**, *6*, 1609−1634.
(462) Mihalache, R.; Verbeek, J.; Graczyk, H.; Murashov, V.; van Broekhuizen, P. Occupational Exposure Limits for Manufactured Nanomaterials, A Systematic Review. *Nanotoxicology* **2017**, *11*, 7−19.
(463) Jeliazkova, N.; Longhin, E.; El Yamani, N.; Runden-Pran, E.; Moschini, E.; Serchi, T.; Vrcek, I. V.; Burgum, M. J.; Doak, S. H.; Cimpan, M. R.; Rios-Mondragon, I.; Cimpan, E.; Battistelli, C. L.; Bossa, C.; Tsekovska, R.; Drobne, D.; Novak, S.; Repar, N.; Ammar, A.; Nymark, P.; et al. A Template Wizard for the Cocreation of Machine-Readable Data-Reporting to Harmonize the Evaluation of (Nano)materials. *Nat. Protoc.* **2024**, *19*, 2642.
(464) Hansen, S. F.; Arvidsson, R.; Nielsen, M. B.; Hansen, O. F. H.; Clausen, L. P. W.; Baun, A.; Boldrin, A. Nanotechnology Meets Circular Economy. *Nat. Nanotechnol.* **2022**, *17*, 682−685.
(465) Abánades Lázaro, I.; Chen, X.; Ding, M.; Eskandari, A.; Fairen-Jimenez, D.; Giménez-Marqués, M.; Gref, R.; Lin, W.; Luo, T.; Forgan, R. S. Metal-Organic Frameworks for Biological Applications. *Nat. Rev. Methods Primers* **2024**, *4*, 42.
(466) *SARS-CoV-2 Research Grade Test Material*. https://www.nist.gov/programs-projects/sars-cov-2-research-grade-test-material (accessed 2025 March 16).
(467) Editors. COVID-19 Validates Science-Industry Collaboration. *Nature* **2021**, *594*, 302−302.
(468) Druedahl, L. C.; Minssen, T.; Price, W. N. Collaboration in Times of Crisis: A Study on COVID-19 Vaccine R&D Partnerships. *Vaccine* **2021**, *39*, 6291−6295.
(469) Collins, F.; Adam, S.; Colvis, C.; Desrosiers, E.; Draghia-Akli, R.; Fauci, A.; Freire, M.; Gibbons, G.; Hall, M.; Hughes, E.; Jansen, K.; Kurilla, M.; Lane, H. C.; Lowy, D.; Marks, P.; Menetski, J.; Pao, W. L.; Perez-Stable, E.; Purcell, L.; Read, S.; et al. The NIH-Led Research Response to COVID-19 Investment, Collaboration, and Coordination Have Been Key. *Science* **2023**, *379*, 441−444.
(470) Ho, L. W. C.; Chan, C. K. W.; Han, R.; Lau, Y. F. Y.; Li, H.; Ho, Y. P.; Zhuang, X.; Choi, C. H. J. Mammalian Cells Exocytose Alkylated Gold Nanoparticles *via* Extracellular Vesicles. *ACS Nano* **2022**, *16*, 2032−2045.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

(471) Roerig, J.; Schulz-Siegmund, M. Standardization Approaches for Extracellular Vesicle Loading with Oligonucleotides and Biologics. *Small* **2023**, *19*, e2301763.

(472) Doricchi, A.; Platnich, C. M.; Gimpel, A.; Horn, F.; Earle, M.; Lanzavecchia, G.; Cortajarena, A. L.; Liz-Marzán, L. M.; Liu, N.; Heckel, R.; Grass, R. N.; Krahne, R.; Keyser, U. F.; Garoli, D. Emerging Approaches to DNA Data Storage: Challenges and Prospects. *ACS Nano* **2022**, *16*, 17552−17571.

(473) *Hardware for Deep Learning*. https://www.nvidia.com/en-us/on-demand/session/hotchips2023-keynote/ (accessed 2025 March 17).

(474) Sangwan, V. K.; Hersam, M. C. Neuromorphic Nanoelectronic Materials. *Nat. Nanotechnol.* **2020**, *15*, 517−528.

(475) Yi, L.; Tan, H. Q.; Hou, B.; Liu, X. X-Ray-to-NIR Multi-Wavelength Imaging through Stochastic Photoluminescence and Compressed Encoding. *Matter* **2024**, *7*, 2431−2447.

(476) Bian, H.; Goh, Y. Y.; Liu, Y.; Ling, H.; Xie, L.; Liu, X. Stimuli-Responsive Memristive Materials for Artificial Synapses and Neuromorphic Computing. *Adv. Mater.* **2021**, *33*, 2006469.

(477) Mao, C.; LaBean, T. H.; Reif, J. H.; Seeman, N. C. Logical Computation Using Algorithmic Self-Assembly of DNA Triple-Crossover Molecules. *Nature* **2000**, *407*, 493−496.

(478) Rothemund, P. W. K.; Papadakis, N.; Winfree, E. Algorithmic Self-Assembly of DNA Sierpinski Triangles. *PLoS Biol.* **2004**, *2*, e424.

(479) Zhang, C.; Wu, R.; Sun, F.; Lin, Y.; Liang, Y.; Teng, J.; Liu, N.; Ouyang, Q.; Qian, L.; Yan, H. Parallel Molecular Data Storage by Printing Epigenetic Bits on DNA. *Nature* **2024**, *634*, 824−832.

(480) Cafferty, B. J.; Ten, A. S.; Fink, M. J.; Morey, S.; Preston, D. J.; Mrksich, M.; Whitesides, G. M. Storage of Information Using Small Organic Molecules. *ACS Cent. Sci.* **2019**, *5*, 911−916.

(481) Koo, Y.; Lee, H.; Ivanova, T.; Savelev, R. S.; Petrov, M. I.; Kravtsov, V.; Park, K.-D. Nanocavity-Integrated van der Waals Heterobilayers for Nano-excitonic Transistor. *ACS Nano* **2023**, *17*, 4854−4861.

(482) Skripka, A.; Zhang, Z.; Qi, X.; Ursprung, B.; Ercius, P.; Cohen, B. E.; Schuck, P. J.; Jaque, D.; Chan, E. M. Intrinsic Optical Bistability of Photon Avalanching Nanocrystals. *Nat. Photonics* **2025**, *19*, 212−218.

(483) Shao, Y.; Pala, M.; Tang, H.; Wang, B.; Li, J.; Esseni, D.; del Alamo, J. A. Scaled Vertical-Nanowire Heterojunction Tunneling Transistors with Extreme Quantum Confinement. *Nat. Electron.* **2024**, *8*, 157−167.

(484) Daus, A.; Vaziri, S.; Chen, V.; Köroğlu, Ç.; Grady, R. W.; Bailey, C. S.; Lee, H. R.; Schauble, K.; Brenner, K.; Pop, E. High-Performance Flexible Nanoscale Transistors Based on Transition Metal Dichalcogenides. *Nat. Electron.* **2021**, *4*, 495−501.

(485) Gan, X.; Englund, D.; Van Thourhout, D.; Zhao, J. 2D Materials-Enabled Optical Modulators: From Visible to Terahertz Spectral Range. *Appl. Phys. Rev.* **2022**, *9*, 021302.

(486) Huang, X.; Liu, C.; Zhou, P. 2D Semiconductors for Specific Electronic Applications: From Device to System. *npj 2D Mater. Appl.* **2022**, *6*, 51.

(487) Chen, J.-h.; Xiong, Y.-f.; Xu, F.; Lu, Y.-q. Silica Optical Fiber Integrated with Two-Dimensional Materials: Towards Opto-Electro-Mechanical Technology. *Light Sci. Appl.* **2021**, *10*, 78.

(488) Dwivedi, N.; Ott, A. K.; Sasikumar, K.; Dou, C.; Yeo, R. J.; Narayanan, B.; Sassi, U.; Fazio, D. D.; Soavi, G.; Dutta, T.; Balci, O.; Shinde, S.; Zhang, J.; Katiyar, A. K.; Keatley, P. S.; Srivastava, A. K.; Sankaranarayanan, S. K. R. S.; Ferrari, A. C.; Bhatia, C. S. Graphene Overcoats for Ultra-High Storage Density Magnetic Media. *Nat. Commun.* **2021**, *12*, 2854.

(489) Aftab, S.; Hussain, S.; Al-Kahtani, A. A. Latest Innovations in 2D Flexible Nanoelectronics. *Adv. Mater.* **2023**, *35*, 2301280.

(490) Ding, L.; Siew, S. Y.; Ang, T. Y. L.; Li, Q.; Zhu, S.; Zhou, Y.; Paniagua-Dominguez, R.; Chu, H.-S.; Lim, S. T.; Png, C. E.; Kuznetsov, A. I. Silicon Nanoantennas for Ultra-Compact, High-Speed and Low-Power Consumption Electro-Optic Modulators. *Laser Photonics Rev.* **2024**, *18*, 2301068.

(491) Lin, X.; Han, Y.; Zhu, J.; Wu, K. Room-Temperature Coherent Optical Manipulation of Hole Spins in Solution-Grown Perovskite Quantum Dots. *Nat. Nanotechnol.* **2023**, *18*, 124−130.

(492) Karli, Y.; Vajner, D. A.; Kappe, F.; Hagen, P. C. A.; Hansen, L. M.; Schwarz, R.; Bracht, T. K.; Schimpf, C.; Covre da Silva, S. F.; Walther, P.; Rastelli, A.; Axt, V. M.; Loredo, J. C.; Remesh, V.; Heindel, T.; Reiter, D. E.; Weihs, G. Controlling the Photon Number Coherence of Solid-State Quantum Light Sources for Quantum cryptography. *npj Quantum Inf.* **2024**, *10*, 17.

(493) Meng, Y.; Chen, Y.; Lu, L.; Ding, Y.; Cusano, A.; Fan, J. A.; Hu, Q.; Wang, K.; Xie, Z.; Liu, Z.; Yang, Y.; Liu, Q.; Gong, M.; Xiao, Q.; Sun, S.; Zhang, M.; Yuan, X.; Ni, X. Optical Meta-Waveguides for Integrated Photonics and Beyond. *Light Sci. Appl.* **2021**, *10*, 235.

(494) Bandyopadhyay, S.; Sludds, A.; Krastanov, S.; Hamerly, R.; Harris, N.; Bunandar, D.; Streshinsky, M.; Hochberg, M.; Englund, D. Single-Chip Photonic Deep Neural Network with Forward-Only Training. *Nat. Photonics* **2024**, *18*, 1335−1343.

(495) Awschalom, D.; Berggren, K. K.; Bernien, H.; Bhave, S.; Carr, L. D.; Davids, P.; Economou, S. E.; Englund, D.; Faraon, A.; Fejer, M.; Guha, S.; Gustafsson, M. V.; Hu, E.; Jiang, L.; Kim, J.; Korzh, B.; Kumar, P.; Kwiat, P. G.; Lončar, M.; Lukin, M. D.; et al. Development of Quantum Interconnects (QuICs) for Next-Generation Information Technologies. *PRX Quantum* **2021**, *2*, 017002.

(496) *Sustainable Development Goals Report 2023*. https://unstats.un.org/sdgs/report/2023/ (accessed 2024 November 9).

(497) Chariou, P. L.; Steinmetz, N. F. Delivery of Pesticides to Plant Parasitic Nematodes Using Tobacco Mild Green Mosaic Virus as a Nanocarrier. *ACS Nano* **2017**, *11*, 4719−4730.

(498) Zhang, H.; Cao, Y.; Xu, D.; Goh, N. S.; Demirer, G. S.; Cestellos-Blanco, S.; Chen, Y.; Landry, M. P.; Yang, P. Gold-Nanocluster-Mediated Delivery of siRNA to Intact Plant Cells for Efficient Gene Knockdown. *Nano Lett.* **2021**, *21*, 5859−5866.

(499) Buriak, J. M.; Liz-Marzán, L. M.; Parak, W. J.; Chen, X. Nano and Plants. *ACS Nano* **2022**, *16*, 1681−1684.

(500) Wang, D.; Saleh, N. B.; Byro, A.; Zepp, R.; Sahle-Demessie, E.; Luxton, T. P.; Ho, K. T.; Burgess, R. M.; Flury, M.; White, J. C.; Su, C. Nano-Enabled Pesticides for Sustainable Agriculture and Global Food Security. *Nat. Nanotechnol.* **2022**, *17*, 347−360.

(501) Squire, H. J.; Tomatz, S.; Voke, E.; González-Grandío, E.; Landry, M. The Emerging Role of Nanotechnology in Plant Genetic Engineering. *Nat. Rev. Bioeng.* **2023**, *1*, 314−328.

(502) Islam, M. R.; Youngblood, M.; Kim, H.-I.; González-Gamboa, I.; Monroy-Borrego, A. G.; Caparco, A. A.; Lowry, G. V.; Steinmetz, N. F.; Giraldo, J. P. DNA Delivery by Virus-Like Nanocarriers in Plant Cells. *Nano Lett.* **2024**, *24*, 7833−7842.

(503) Buchman, J. T.; Elmer, W. H.; Ma, C.; Landy, K. M.; White, J. C.; Haynes, C. L. Chitosan-Coated Mesoporous Silica Nanoparticle Treatment of *Citrullus lanatus* (Watermelon): Enhanced Fungal Disease Suppression and Modulated Expression of Stress-Related Genes. *ACS Sustain. Chem. Eng.* **2019**, *7*, 19649−19659.

(504) Borgatta, J.; Shen, Y.; Tamez, C.; Green, C.; Hedlund Orbeck, J. K.; Cahill, M. S.; Protter, C.; Deng, C.; Wang, Y.; Elmer, W.; White, J. C.; Hamers, R. J. Influence of CuO Nanoparticle Aspect Ratio and Surface Charge on Disease Suppression in Tomato (*Solanum lycopersicum*). *J. Agric. Food Chem.* **2023**, *71*, 9644−9655.

(505) Tuga, B.; O'Keefe, T.; Deng, C.; Ligocki, A. T.; White, J. C.; Haynes, C. L. Designing Nanoparticles for Sustainable Agricultural Applications. *Trends Chem.* **2023**, *5*, 814−826.

(506) Dimkpa, C. O.; Haynes, C. L.; White, J. C. Reducing Greenhouse Gas Emissions with Nanofertilizers. *Nat. Sustain.* **2024**, *7*, 696−697.

(507) Vaidya, S.; Deng, C.; Wang, Y.; Zuverza-Mena, N.; Dimkpa, C.; White, J. C. Nanotechnology in Agriculture: A Solution to Global Food Insecurity in a Changing Climate? *Nanoimpact* **2024**, *34*, 100502.

(508) Perera, M. J. L.; Yakandawala, D. M. D.; Seneweera, S. Nanoclay Composites as Agrochemical Carriers. *Clay Composites: Environmental Applications*, Vithanage, M.; Lazzara, G.; Rajapaksha, A. U., Ed.; Springer Singapore, 2023; pp 543−557.

(509) Abd-Elsalam, K. A.; Mehmood, M. A.; Ashfaq, M.; Abdelkhalek, T. E.; Hassan, R. K.; Ravichandran, M. Liquid Nanoclay: Synthesis and Applications to Transform an Arid Desert into Fertile Land. *Soil Syst.* **2024**, *8*, 73.
(510) Dhanapal, A. R.; Thiruvengadam, M.; Vairavanathan, J.; Venkidasamy, B.; Easwaran, M.; Ghorbanpour, M. Nanotechnology Approaches for the Remediation of Agricultural Polluted Soils. *ACS Omega* **2024**, *9*, 13522−13533.
(511) Paul, R.; Saville, A. C.; Hansel, J. C.; Ye, Y.; Ball, C.; Williams, A.; Chang, X.; Chen, G.; Gu, Z.; Ristaino, J. B.; Wei, Q. Extraction of Plant DNA by Microneedle Patch for Rapid Detection of Plant Diseases. *ACS Nano* **2019**, *13*, 6540−6549.
(512) Maurer-Jones, M. A.; Gunsolus, I. L.; Murphy, C. J.; Haynes, C. L. Toxicity of Engineered Nanoparticles in the Environment. *Anal. Chem.* **2013**, *85*, 3036−3049.
(513) Paramo, L. A.; Feregrino-Pérez, A. A.; Guevara, R.; Mendoza, S.; Esquivel, K. Nanoparticles in Agroindustry: Applications, Toxicity, Challenges, and Trends. *Nanomaterials* **2020**, *10*, 1654.
(514) Khan, M.; Khan, M. S. A.; Borah, K. K.; Goswami, Y.; Hakeem, K. R.; Chakrabartty, I. The Potential Exposure and Hazards of Metal-Based Nanoparticles on Plants and Environment, with Special Emphasis on ZnO NPs, TiO_2 NPs, and AgNPs: A Review. *Environ. Adv.* **2021**, *6*, 100128.
(515) *Agriculture, Food Systems, and Rural Communities*. Fifth National Climate Assessment, DOI: 10.7930/NCA5.2023.CH11 (accessed 2024 November 9).
(516) Berliner, A.; Hilzinger, J.; Abel, A.; McNulty, M.; Makrygiorgos, G.; Averesch, N.; Sen Gupta, S.; Benvenuti, A.; Caddell, D.; Cestellos-Blanco, S.; Doloman, A.; Friedline, S.; Ho, D.; Gu, W.; Hill, A.; Kusuma, P.; Lipsky, I.; Mirkovic, M.; Meraz, J.; Arkin, A.; et al. Towards a Biomanufactory on Mars. *Front. Astron. Space Sci.* **2021**, *8*, 711550.
(517) Hanikel, N.; Prevot, M. S.; Yaghi, O. M. MOF Water Harvesters. *Nat. Nanotechnol.* **2020**, *15*, 348−355.
(518) Zhang, S.; Fu, J.; Das, S.; Ye, K.; Zhu, W.; Ben, T. Crystalline Porous Organic Salt for Ultrarapid Adsorption/Desorption-Based Atmospheric Water Harvesting by Dual Hydrogen Bond System. *Angew. Chem. Int. Ed.* **2022**, *61*, e202208660.
(519) Nguyen, H. L. Covalent Organic Frameworks for Atmospheric Water Harvesting. *Adv. Mater.* **2023**, *35*, 2300018.
(520) Lin, H.; Yang, Y.; Hsu, Y.-C.; Zhang, J.; Welton, C.; Afolabi, I.; Loo, M.; Zhou, H.-C. Metal-Organic Frameworks for Water Harvesting and Concurrent Carbon Capture: A Review for Hygroscopic Materials. *Adv. Mater.* **2024**, *36*, 2209073.
(521) Hanikel, N.; Pei, X.; Chheda, S.; Lyu, H.; Jeong, W.; Sauer, J.; Gagliardi, L.; Yaghi, O. M. Evolution of Water Structures in Metal-Organic Frameworks for Improved Atmospheric Water Harvesting. *Science* **2021**, *374*, 454−459.
(522) Shi, W.; Guan, W.; Lei, C.; Yu, G. Sorbents for Atmospheric Water Harvesting: From Design Principles to Applications. *Angew. Chem. Int. Ed.* **2022**, *134*, e202211267.
(523) Li, T.; Yan, T.; Wang, P.; Xu, J.; Huo, X.; Bai, Z.; Shi, W.; Yu, G.; Wang, R. Scalable and Efficient Solar-Driven Atmospheric Water Harvesting Enabled by Bidirectionally Aligned and Hierarchically Structured Nanocomposites. *Nat. Water* **2023**, *1*, 971−981.
(524) Lee, K. P.; Arnot, T. C.; Mattia, D. A Review of Reverse Osmosis Membrane Materials for Desalination—Development to Date and Future Potential. *J. Membr. Sci.* **2011**, *370*, 1−22.
(525) Buonomenna, M. G. Nano-Enhanced Reverse Osmosis Membranes. *Desalination* **2013**, *314*, 73−88.
(526) Kim, H. J.; Choi, K.; Baek, Y.; Kim, D.-G.; Shim, J.; Yoon, J.; Lee, J.-C. High-Performance Reverse Osmosis CNT/Polyamide Nanocomposite Membrane by Controlled Interfacial Interactions. *ACS Appl. Mater. Interfaces* **2014**, *6*, 2819−2829.
(527) Safarpour, M.; Khataee, A.; Vatanpour, V. Thin Film Nanocomposite Reverse Osmosis Membrane Modified by Reduced Graphene Oxide/TiO_2 with Improved Desalination Performance. *J. Membr. Sci.* **2015**, *489*, 43−54.
(528) Plessl, K.; Russ, A.; Vollprecht, D. Application and Development of Zero-Valent Iron (ZVI) for Groundwater and Wastewater Treatment. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 6913−6928.
(529) Wang, C.; Yu, C. Detection of Chemical Pollutants in Water Using Gold Nanoparticles as Sensors: A Review. *Rev. Anal. Chem.* **2013**, *32*, 1−14.
(530) McQueen, A. D.; Ballentine, M. L.; May, L. R.; Laber, C. H.; Das, A.; Bortner, M. J.; Kennedy, A. J. Photocatalytic Degradation of Polycyclic Aromatic Hydrocarbons in Water by 3D Printed TiO_2 Composites. *ACS ES&TW* **2022**, *2*, 137−147.
(531) Yusoff, N. H. M.; Teo, L.-R. I.; Phang, S. J.; Wong, V.-L.; Cheah, K. H.; Lim, S.-S. Recent Advances in Polymer-based 3D Printing for Wastewater Treatment Application: An Overview. *Chem. Eng. J.* **2022**, *429*, 132311.
(532) Barman, S. R.; Gavit, P.; Chowdhury, S.; Chatterjee, K.; Nain, A. 3D-Printed Materials for Wastewater Treatment. *JACS Au* **2023**, *3*, 2930−2947.
(533) Nandwana, V.; Ribet, S. M.; Reis, R. D.; Kuang, Y.; More, Y.; Dravid, V. P. OHM Sponge: A Versatile, Efficient, and Ecofriendly Environmental Remediation Platform. *Ind. Eng. Chem. Res.* **2020**, *59*, 10945−10954.
(534) Ribet, S. M.; Shindel, B.; dos Reis, R.; Nandwana, V.; Dravid, V. P. Phosphate Elimination and Recovery Lightweight (PEARL) membrane: A Sustainable Environmental Remediation Approach. *Proc. Natl. Acad. Sci. U.S.A.* **2021**, *118*, e2102583118.
(535) Matuszewski, K. E.; Shindel, B.; Nandwana, V.; Dravid, V. P. Rinse, Recover, Repeat: pH-Assisted Selective Extraction of Phosphate and Metals with a Sponge Nanocomposite. *ACS ES&T Water* **2025**, *5*, 1055−1063.
(536) Lu, W.; Qin, X.; Liu, S.; Chang, G.; Zhang, Y.; Luo, Y.; Asiri, A. M.; Al-Youbi, A. O.; Sun, X. Economical, Green Synthesis of Fluorescent Carbon Nanoparticles and Their Use as Probes for Sensitive and Selective Detection of Mercury(II) Ions. *Anal. Chem.* **2012**, *84*, 5351−5357.
(537) Howes, P. D.; Chandrawati, R.; Stevens, M. M. Colloidal Nanoparticles as Advanced Biological Sensors. *Science* **2014**, *346*, 1247390.
(538) Devi, P.; Rajput, P.; Thakur, A.; Kim, K.-H.; Kumar, P. Recent Advances in Carbon Quantum Dot-Based Sensing of Heavy Metals in Water. *TrAC* **2019**, *114*, 171−195.
(539) Wang, L.; Ma, W.; Xu, L.; Chen, W.; Zhu, Y.; Xu, C.; Kotov, N. A. Nanoparticle-Based Environmental Sensors. *Mater. Sci. Eng. R: Rep.* **2010**, *70*, 265−274.
(540) Basarir, F.; Madani, Z.; Vapaavuori, J. Recent Advances in Silver Nanowire Based Flexible Capacitive Pressure Sensors: From Structure, Fabrication to Emerging Applications. *Adv. Mater. Interfaces* **2022**, *9*, 2200866.
(541) Ussler, W., Iii; Doucette, G. J.; Preston, C. M.; Weinstock, C.; Allaf, N.; Roman, B.; Jensen, S.; Yamahara, K.; Lingerfelt, L. A.; Mikulski, C. M.; Hobson, B. W.; Kieft, B.; Raanan, B.-Y.; Zhang, Y.; Errera, R. M.; Ruberg, S. A.; Den Uyl, P. A.; Goodwin, K. D.; Soelberg, S. D.; Furlong, C. E.; et al. Underway Measurement of Cyanobacterial Microcystins Using a Surface Plasmon Resonance Sensor on an Autonomous Underwater Vehicle. *Limnol. Oceanogr.: Methods* **2024**, *22*, 681−699.
(542) *NORMAN Database System*. https://www.norman-network.com/nds/ (accessed 2025 January 30).
(543) *Environmental Topics*. United States Environmental Protection Agency, 2024. https://www.epa.gov/environmental-topics (accessed 2024−11−06).
(544) Martínez, J. H.; Romero, S.; Ramasco, J. J.; Estrada, E. The World-Wide Waste Web. *Nat. Commun.* **2022**, *13*, 1615.
(545) Asghar, N.; Hussain, A.; Nguyen, D. A.; Ali, S.; Hussain, I.; Junejo, A.; Ali, A. Advancement in Nanomaterials for Environmental Pollutants Remediation: A Systematic Review on Bibliometrics Analysis, Material Types, Synthesis Pathways, and Related Mechanisms. *J. Nanobiotechnology* **2024**, *22*, 26.

(546) Wu, M.; Ma, B.; Pan, T.; Chen, S.; Sun, J. Silver-Nanoparticle-Colored Cotton Fabrics with Tunable Colors and Durable Antibacterial and Self-Healing Superhydrophobic Properties. *Adv. Funct. Mater.* **2016**, *26*, 569−576.
(547) Riduan, S. N.; Zhang, Y. Nanostructured Surfaces with Multimodal Antimicrobial Action. *Acc. Chem. Res.* **2021**, *54*, 4508−4517.
(548) Huang, X.; Auffan, M.; Eckelman, M. J.; Elimelech, M.; Kim, J.-H.; Rose, J.; Zuo, K.; Li, Q.; Alvarez, P. J. J. Trends, Risks and Opportunities in Environmental Nanotechnology. *Nat. Rev. Earth Environ.* **2024**, *5*, 572−587.
(549) Christou, A.; Beretsou, V. G.; Iakovides, I. C.; Karaolia, P.; Michael, C.; Benmarhnia, T.; Chefetz, B.; Donner, E.; Gawlik, B. M.; Lee, Y.; Lim, T. T.; Lundy, L.; Maffettone, R.; Rizzo, L.; Topp, E.; Fatta-Kassinos, D. Sustainable Wastewater Reuse for Agriculture. *Nat. Rev. Earth Environ.* **2024**, *5*, 504−521.
(550) Lou, M.; Bao, J. L.; Zhou, L.; Naidu, G. N.; Robatjazi, H.; Bayles, A. I.; Everitt, H. O.; Nordlander, P.; Carter, E. A.; Halas, N. J. Direct H_2S Decomposition by Plasmonic Photocatalysis: Efficient Remediation Plus Sustainable Hydrogen Production. *ACS Energy Lett.* **2022**, *7*, 3666−3674.
(551) Lou, M.; Bayles, A.; Everitt, H. O.; Halas, N. J. Selective Photodetoxification of a Sulfur Mustard Simulant Using Plasmonic Aluminum Nanoparticles. *Nano Lett.* **2022**, *22*, 7699−7705.
(552) Yuan, Y.; Zhou, L.; Robatjazi, H.; Bao, J. L.; Zhou, J.; Bayles, A.; Yuan, L.; Lou, M.; Lou, M.; Khatiwada, S.; Carter, E. A.; Nordlander, P.; Halas, N. J. Earth-Abundant Photocatalyst for H_2 Generation from NH_3 with Light-Emitting Diode Illumination. *Science* **2022**, *378*, 889−893.
(553) Khin, M. M.; Nair, A. S.; Babu, V. J.; Murugan, R.; Ramakrishna, S. A Review on Nanomaterials for Environmental Remediation. *Energy Environ. Sci.* **2012**, *5*, 8075−8109.
(554) Zhou, H.-C.; Long, J. R.; Yaghi, O. M. Introduction to Metal-Organic Frameworks. *Chem. Rev.* **2012**, *112*, 673−674.
(555) Islamoglu, T.; Chen, Z.; Wasson, M. C.; Buru, C. T.; Kirlikovali, K. O.; Afrin, U.; Mian, M. R.; Farha, O. K. Metal-Organic Frameworks against Toxic Chemicals. *Chem. Rev.* **2020**, *120*, 8130−8160.
(556) Kirlikovali, K. O.; Chen, Z.; Islamoglu, T.; Hupp, J. T.; Farha, O. K. Zirconium-Based Metal-Organic Frameworks for the Catalytic Hydrolysis of Organophosphorus Nerve Agents. *ACS Appl. Mater. Interfaces* **2020**, *12*, 14702−14720.
(557) Chen, Z.; Kirlikovali, K. O.; Li, P.; Farha, O. K. Reticular Chemistry for Highly Porous Metal-Organic Frameworks: The Chemistry and Applications. *Acc. Chem. Res.* **2022**, *55*, 579−591.
(558) Liu, Y.; Howarth, A. J.; Vermeulen, N. A.; Moon, S.-Y.; Hupp, J. T.; Farha, O. K. Catalytic Degradation of Chemical Warfare Agents and their Simulants by Metal-Organic Frameworks. *Coord. Chem. Rev.* **2017**, *346*, 101−111.
(559) Seifrid, M.; Pollice, R.; Aguilar-Granda, A.; Morgan Chan, Z.; Hotta, K.; Ser, C. T.; Vestfrid, J.; Wu, T. C.; Aspuru-Guzik, A. Autonomous Chemical Experiments: Challenges and Perspectives on Establishing a Self-Driving Lab. *Acc. Chem. Res.* **2022**, *55*, 2454−2466.
(560) Bran, A. M.; Cox, S.; Schilter, O.; Baldassari, C.; White, A. D.; Schwaller, P. Augmenting Large Language Models with Chemistry Tools. *Nat. Mach. Intell.* **2024**, *6*, 525−535.
(561) Urso, M.; Ussia, M.; Pumera, M. Smart Micro- and Nanorobots for Water Purification. *Nature Reviews Bioengineering* **2023**, *1*, 236−251.
(562) Munyaneza, N. E.; Posada, C.; Xu, Z.; De Altin Popiolek, V.; Paddock, G.; McKee, C.; Liu, G. A Generic Platform for Upcycling Polystyrene to Aryl Ketones and Organosulfur Compounds. *Angew. Chem. Int. Ed.* **2023**, *62*, e202307042.
(563) Boamah, M. D.; Lozier, E. H.; Kim, J.; Ohno, P. E.; Walker, C. E.; Miller, T. F.; Geiger, F. M. Energy Conversion *via* Metal Nanolayers. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116*, 16210−16215.
(564) Barua, A.; Salauddin Rasel, M. Advances and Challenges in Ocean Wave Energy Harvesting. *Sustain. Energy Technol. Assessments* **2024**, *61*, 103599.
(565) Lu, Z.-Q.; Zhao, L.; Fu, H.-L.; Yeatman, E.; Ding, H.; Chen, L.-Q. Ocean Wave Energy Harvesting with High Energy Density and Self-Powered Monitoring System. *Nat. Commun.* **2024**, *15*, 6513.
(566) Zhang, F.; Zeng, M.; Yappert, R. D.; Sun, J.; Lee, Y.-H.; LaPointe, A. M.; Peters, B.; Abu-Omar, M. M.; Scott, S. L. Polyethylene Upcycling to Long-Chain Alkylaromatics by Tandem Hydrogenolysis/Aromatization. *Science* **2020**, *370*, 437−441.
(567) Conk, R. J.; Hanna, S.; Shi, J. X.; Yang, J.; Ciccia, N. R.; Qi, L.; Bloomer, B. J.; Heuvel, S.; Wills, T.; Su, J.; Bell, A. T.; Hartwig, J. F. Catalytic Deconstruction of Waste Polyethylene with Ethylene to Form Propylene. *Science* **2022**, *377*, 1561−1566.
(568) Sayed, E. T.; Olabi, A. G.; Alami, A. H.; Radwan, A.; Mdallal, A.; Rezk, A.; Abdelkareem, M. A. Renewable Energy and Energy Storage Systems. *Energies* **2023**, *16*, 1415.
(569) Aricò, A. S.; Bruce, P.; Scrosati, B.; Tarascon, J.-M.; van Schalkwijk, W. Nanostructured Materials for Advanced Energy Conversion and Storage Devices. *Nat. Mater.* **2005**, *4*, 366−377.
(570) Zhang, Y.; Liu, N. Nanostructured Electrode Materials for High-Energy Rechargeable Li, Na and Zn Batteries. *Chem. Mater.* **2017**, *29*, 9589−9604.
(571) Nam, K. W.; Park, S. S.; dos Reis, R.; Dravid, V. P.; Kim, H.; Mirkin, C. A.; Stoddart, J. F. Conductive 2D Metal-Organic Framework for High-Performance Cathodes in Aqueous Rechargeable Zinc Batteries. *Nat. Commun.* **2019**, *10*, 4948.
(572) Pomerantseva, E.; Bonaccorso, F.; Feng, X.; Cui, Y.; Gogotsi, Y. Energy Storage: The Future Enabled by Nanomaterials. *Science* **2019**, *366*, eaan8285.
(573) Li, B.; Yu, M.; Li, Z.; Yu, C.; Li, Q.; Wang, H. Three-Dimensional Activated Carbon Nanosheets Modified by Graphitized Carbon Dots: One-Step Alkali Pyrolysis Preparation and Supercapacitor Applications. *J. Energy Storage* **2022**, *51*, 104515.
(574) Wang, Y.; Yang, J.; Liu, S.; Che, X.; He, S.; Liu, Z.; Wang, M.; Wang, X.; Qiu, J. 3D Graphene-Like Oxygen and Sulfur-Doped Porous Carbon Nanosheets with Multilevel Ion Channels for High-Performance Aqueous Zn-Ion Storage. *Carbon* **2023**, *201*, 624−632.
(575) Corma, A. From Microporous to Mesoporous Molecular Sieve Materials and Their Use in Catalysis. *Chem. Rev.* **1997**, *97*, 2373−2420.
(576) Morris, R. E.; Wheatley, P. S. Gas Storage in Nanoporous Materials. *Angew. Chem. Int. Ed.* **2008**, *47*, 4966−4981.
(577) Lu, G.; Li, S.; Guo, Z.; Farha, O. K.; Hauser, B. G.; Qi, X.; Wang, Y.; Wang, X.; Han, S.; Liu, X.; DuChene, J. S.; Zhang, H.; Zhang, Q.; Chen, X.; Ma, J.; Loo, S. C. J.; Wei, W. D.; Yang, Y.; Hupp, J. T.; Huo, F. Imparting Functionality to a Metal-Organic Framework Material by Controlled Nanoparticle Encapsulation. *Nat. Chem.* **2012**, *4*, 310−316.
(578) Kumar, K. V.; Preuss, K.; Titirici, M.-M.; Rodríguez-Reinoso, F. Nanoporous Materials for the Onboard Storage of Natural Gas. *Chem. Rev.* **2017**, *117*, 1796−1825.
(579) Liu, T.; Zhou, Z.; Guo, Y.; Guo, D.; Liu, G. Block Copolymer Derived Uniform Mesopores Enable Ultrafast Electron and Ion Transport at High Mass Loadings. *Nat. Commun.* **2019**, *10*, 675.
(580) Zhou, Z.; Liu, T.; Khan, A. U.; Liu, G. Block Copolymer-Based Porous Carbon Fibers. *Sci. Adv.* **2019**, *5*, eaau6852.
(581) Connolly, B. M.; Madden, D. G.; Wheatley, A. E. H.; Fairen-Jimenez, D. Shaping the Future of Fuel: Monolithic Metal-Organic Frameworks for High-Density Gas Storage. *J. Am. Chem. Soc.* **2020**, *142*, 8541−8549.
(582) Liu, T.; Serrano, J.; Elliott, J.; Yang, X.; Cathcart, W.; Wang, Z.; He, Z.; Liu, G. Exceptional Capacitive Deionization Rate and Capacity by Block Copolymer-Based Porous Carbon Fibers. *Sci. Adv.* **2020**, *6*, eaaz0906.
(583) Miao, J.; Lang, Z.; Xue, T.; Li, Y.; Li, Y.; Cheng, J.; Zhang, H.; Tang, Z. Revival of Zeolite-Templated Nanocarbon Materials: Recent Advances in Energy Storage and Conversion. *Adv. Sci.* **2020**, *7*, 2001335.
(584) Peng, P.; Anastasopoulou, A.; Brooks, K.; Furukawa, H.; Bowden, M. E.; Long, J. R.; Autrey, T.; Breunig, H. Cost and Potential

of Metal-Organic Frameworks for Hydrogen Back-Up Power Supply. *Nat. Energy* **2022**, *7*, 448−458.
(585) Sengupta, D.; Melix, P.; Bose, S.; Duncan, J.; Wang, X.; Mian, M. R.; Kirlikovali, K. O.; Joodaki, F.; Islamoglu, T.; Yildirim, T.; Snurr, R. Q.; Farha, O. K. Air-Stable Cu(I) Metal-Organic Framework for Hydrogen Storage. *J. Am. Chem. Soc.* **2023**, *145*, 20492−20502.
(586) Kapelewski, M. T.; Runčevski, T.; Tarver, J. D.; Jiang, H. Z. H.; Hurst, K. E.; Parilla, P. A.; Ayala, A.; Gennett, T.; FitzGerald, S. A.; Brown, C. M.; Long, J. R. Record High Hydrogen Storage Capacity in the Metal-Organic Framework Ni_2(m-dobdc) at Near-Ambient Temperatures. *Chem. Mater.* **2018**, *30*, 8179−8189.
(587) Anastasopoulou, A.; Furukawa, H.; Barnett, B. R.; Jiang, H. Z. H.; Long, J. R.; Breunig, H. M. Technoeconomic Analysis of Metal-Organic Frameworks for Bulk Hydrogen Transportation. *EES* **2021**, *14*, 1083−1094.
(588) Jacoby, M. NuMat Technologies. *C&EN Global Enterprise* **2016**, *94*, 32−32.
(589) Zhao, J.; Holmes, M. A.; Osterloh, F. E. Quantum Confinement Controls Photocatalysis: A Free Energy Analysis for Photocatalytic Proton Reduction at CdSe Nanocrystals. *ACS Nano* **2013**, *7*, 4316−4325.
(590) Fernando, K. A. S.; Sahu, S.; Liu, Y.; Lewis, W. K.; Guliants, E. A.; Jafariyan, A.; Wang, P.; Bunker, C. E.; Sun, Y.-P. Carbon Quantum Dots and Applications in Photocatalytic Energy Conversion. *ACS Appl. Mater. Interfaces* **2015**, *7*, 8363−8376.
(591) Pannir-Sivajothi, S.; Campos-Gonzalez-Angulo, J. A.; Martínez-Martínez, L. A.; Sinha, S.; Yuen-Zhou, J. Driving Chemical Reactions with Polariton Condensates. *Nat. Commun.* **2022**, *13*, 1645.
(592) Li, H.; Quan, Q.; Wong, C.-Y.; Ho, J. C. Spin-Selective Catalysts for Oxygen-Involved Electrocatalysis. *Adv. Energy Sustain. Res.* **2025**, *6*, 2400326.
(593) Ni, B.; Wang, X. Face the Edges: Catalytic Active Sites of Nanomaterials. *Adv. Sci.* **2015**, *2*, 1500085.
(594) Kempa, T. J.; Cahoon, J. F.; Kim, S.-K.; Day, R. W.; Bell, D. C.; Park, H.-G.; Lieber, C. M. Coaxial Multishell Nanowires with High-Quality Electronic Interfaces and Tunable Optical Cavities for Ultrathin Photovoltaics. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109*, 1407−1412.
(595) Kempa, T. J.; Lieber, C. M. Semiconductor Nanowire Solar Cells: Synthetic Advances and Tunable Properties. *Pure Appl. Chem.* **2014**, *86*, 13−26.
(596) Zhu, W.; Michalsky, R.; Metin, Ö.; Lv, H.; Guo, S.; Wright, C. J.; Sun, X.; Peterson, A. A.; Sun, S. Monodisperse Au Nanoparticles for Selective Electrocatalytic Reduction of CO_2 to CO. *J. Am. Chem. Soc.* **2013**, *135*, 16833−16836.
(597) Sagawa, M.; Hirosawa, S.; Yamamoto, H.; Fujimura, S.; Matsuura, Y. Nd-Fe-B Permanent-Magnet Materials. *Jpn. J. Appl. Phys.* **1987**, *26*, 785−800.
(598) Balaram, V. Rare Earth Elements: A Review of Applications, Occurrence, Exploration, Analysis, Recycling, and Environmental Impact. *Geosci. Front.* **2019**, *10*, 1285−1303.
(599) Cui, Y.; Melby, E. S.; Mensch, A. C.; Laudadio, E. D.; Hang, M. N.; Dohnalkova, A.; Hu, D.; Hamers, R. J.; Orr, G. Quantitative Mapping of Oxidative Stress Response to Lithium Cobalt Oxide Nanoparticles in Single Cells Using Multiplexed *in situ* Gene Expression Analysis. *Nano Lett.* **2019**, *19*, 1990−1997.
(600) Barrak, H.; Ahmedi, R.; Chevallier, P.; M'nif, A.; Laroche, G.; Hamzaoui, A. H. Highly Efficient Extraction of Rare Earth Elements and Other Ions from Green Phosphoric Acid Medium using TMSEDTA@GO@FeO Core-Shell. *Sep. Purif. Technol.* **2019**, *222*, 145−151.
(601) Deng, B.; Luong, D. X.; Wang, Z.; Kittrell, C.; McHugh, E. A.; Tour, J. M. Urban Mining by Flash Joule Heating. *Nat. Commun.* **2021**, *12*, 5794.
(602) Alharbi, A.; Al-Ahmed, Z. A.; El-Metwaly, N. M.; Shahat, A.; El-Bindary, M. A. A Novel Strategy for Preparing Metal-Organic Framework as a Smart Material for Selective Detection and Efficient Extraction of Pd(II) and Au (III) ions from E-Wastes. *J. Mol. Liq.* **2023**, *369*, 120862.
(603) Hu, Q. H.; Song, A. M.; Gao, X.; Shi, Y. Z.; Jiang, W.; Liang, R. P.; Qiu, J. D. Rationally Designed Nanotrap Structures for Efficient Separation of Rare Earth Elements over a Single Step. *Nat. Commun.* **2024**, *15*, 1558.
(604) Zhao, Z. Z.; Feng, S. C.; Xiao, C. Y.; Luo, J. Q.; Song, W. J.; Wan, Y. H.; Li, S. H. Exploring Ions Selectivity of Nanofiltration Membranes for Rare Earth Wastewater Treatment. *Sep. Purif. Technol.* **2022**, *289*, 120748.
(605) Kujawa, J.; Al Gharabli, S.; Szymczyk, A.; Terzyk, A. P.; Boncel, S.; Knozowska, K.; Li, G. Q.; Kujawski, W. On Membrane-based Approaches for Rare Earths Separation and Extraction - Recent Developments. *Coord. Chem. Rev.* **2023**, *493*, 215340.
(606) Wang, M.; Xiong, Q.; Wang, M.; Lewis, N. H. C.; Ying, D.; Yan, G.; Hoenig, E.; Han, Y.; Lee, O.-S.; Peng, G.; Zhou, H.; Schatz, G. C.; Liu, C. Lanthanide Transport in Angstrom-Scale MoS_2-Based Two-Dimensional Channels. *Sci. Adv.* **2024**, *10*, eadh1330.
(607) Yeh, S. L.; Alexander, D.; Narasimhalu, N.; Koshani, R.; Sheikhi, A. Mussel-Inspired Nanocellulose Coating for Selective Neodymium Recovery. *ACS Appl. Mater. Interfaces* **2023**, *15*, 44154−44166.
(608) Daumann, L. J. A Natural Lanthanide-Binding Protein Facilitates Separation and Recovery of Rare Earth Elements. *ACS Cent. Sci.* **2021**, *7*, 1780−1782.
(609) Hussain, Z.; Kim, S.; Cho, J.; Sim, G.; Park, Y.; Kwon, I. Repeated Recovery of Rare Earth Elements Using a Highly Selective and Thermo-Responsive Genetically Encoded Polypeptide. *Adv. Funct. Mater.* **2022**, *32*, 2109158.
(610) Huang, J.; Wang, Z.; Liang, J.; Li, X.-Y.; Pietryga, J.; Ye, Z.; Smith, P. T.; Kulaksizoglu, A.; McCormick, C. R.; Ki, J.; et al. Accelerating the Pace of Oxygen Evolution Reaction Catalyst Discovery through Megalibraries. *J. Am. Chem. Soc.* **2025**, *147*, 30956−30966.
(611) Balasubramanian, B.; Das, B.; Skomski, R.; Zhang, W. Y.; Sellmyer, D. J. Novel Nanostructured Rare-Earth-Free Magnetic Materials with High Energy Products. *Adv. Mater.* **2013**, *25*, 6090−6093.
(612) Yunphuttha, C.; Porntheeraphat, S.; Midpanon, S.; Wongchaisuwat, A.; Viravathana, P. Improving the Catalytic Activity of Lanthanum Manganese Oxide with Strontium Doping for Hydrogen Peroxide Reduction Reaction in Micro Direct Alcohol-Hydrogen Peroxide Fuel Cell. *J. Power Sources* **2018**, *392*, 251−259.
(613) Ryoo, R.; Kim, J.; Jo, C.; Han, S. W.; Kim, J. C.; Park, H.; Han, J.; Shin, H. S.; Shin, J. W. Rare-Earth-Platinum Alloy Nanoparticles in Mesoporous Zeolite for Catalysis. *Nature* **2020**, *585*, 221.
(614) Roco, M. C.; Bainbridge, W. S. Converging Technologies for Improving Human Performance: Integrating From the Nanoscale. *J. Nanopart. Res.* **2002**, *4*, 281−295.
(615) Dugger, S. A.; Platt, A.; Goldstein, D. B. Drug Development in the Era of Precision Medicine. *Nat. Rev. Drug Discovery* **2018**, *17*, 183−196.
(616) Watson, O. J.; Barnsley, G.; Toor, J.; Hogan, A. B.; Winskill, P.; Ghani, A. C. Global Impact of the First Year of COVID-19 Vaccination: A Mathematical Modeling Study. *Lancet Infect. Dis.* **2022**, *22*, 1293−1302.
(617) Janes, M. E.; Gottlieb, A. P.; Park, K. S.; Zhao, Z.; Mitragotri, S. Cancer Vaccines in the Clinic. *Bioeng. Transl. Med.* **2024**, *9*, e10588.
(618) Shattock, A. J.; Johnson, H. C.; Sim, S. Y.; Carter, A.; Lambach, P.; Hutubessy, R. C. W.; Thompson, K. M.; Badizadegan, K.; Lambert, B.; Ferrari, M. J.; Jit, M.; Fu, H.; Silal, S. P.; Hounsell, R. A.; White, R. G.; Mosser, J. F.; Gaythorpe, K. A. M.; Trotter, C. L.; Lindstrand, A.; O'Brien, K. L.; et al. Contribution of Vaccination to Improved Survival and Health: Modeling 50 Years of the Expanded Programme on Immunization. *Lancet* **2024**, *403*, 2307−2316.
(619) Baden, L. R.; El Sahly, H. M.; Essink, B.; Kotloff, K.; Frey, S.; Novak, R.; Diemert, D.; Spector, S. A.; Rouphael, N.; Creech, C. B.; McGettigan, J.; Khetan, S.; Segall, N.; Solis, J.; Brosz, A.; Fierro, C.; Schwartz, H.; Neuzil, K.; Corey, L.; Gilbert, P.; Janes, H.; Follmann, D.; Marovich, M.; Mascola, J.; Polakowski, L.; Ledgerwood, J.;

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

Graham, B. S.; Bennett, H.; Pajon, R.; Knightly, C.; Leav, B.; Deng, W.; Zhou, H.; Han, S.; Ivarsson, M.; Miller, J.; Zaks, T.; et al. Efficacy and Safety of the mRNA-1273 SARS-CoV-2 Vaccine. *NEJM* **2021**, *384*, 403−416.

(620) Mabrouk, M. T.; Chiem, K.; Rujas, E.; Huang, W.-C.; Jahagirdar, D.; Quinn, B.; Surendran Nair, M.; Nissly, R. H.; Cavener, V. S.; Boyle, N. R.; Sornberger, T. A.; Kuchipudi, S. V.; Ortega, J.; Julien, J.-P.; Martinez-Sobrido, L.; Lovell, J. Lyophilized, Thermostable Spike or RBD Immunogenic Liposomes Induce Protective Immunity Against SARS-CoV-2 in Mice. *Sci. Adv.* **2021**, *7*, eabj1476.

(621) Azharuddin, M.; Zhu, G. H.; Sengupta, A.; Hinkula, J.; Slater, N. K. H.; Patra, H. K. Nano Toolbox in Immune Modulation and Nanovaccines. *Trends Biotechnol* **2022**, *40*, 1195−1212.

(622) Jayathilaka, W. A. D. M.; Qi, K.; Qin, Y.; Chinnappan, A.; Serrano-García, W.; Baskar, C.; Wang, H.; He, J.; Cui, S.; Thomas, S. W.; Ramakrishna, S. Significance of Nanomaterials in Wearables: A Review on Wearable Actuators and Sensors. *Adv. Mater.* **2019**, *31*, 1805921.

(623) Xu, H.; Li, S.; Liu, Y.-S. Nanoparticles in the Diagnosis and Treatment of Vascular Aging and Related Diseases. *Signal transduct. target. ther.* **2022**, *7*, 231.

(624) Ranke, D.; Lee, I.; Gershanok, S. A.; Jo, S.; Trotto, E.; Wang, Y.; Balakrishnan, G.; Cohen-Karni, T. Multifunctional Nanomaterials for Advancing Neural Interfaces: Recording, Stimulation, and Beyond. *Acc. Chem. Res.* **2024**, *57*, 1803−1814.

(625) Kotagama, O. W.; Jayasinghe, C. D.; Abeysinghe, T. Era of Genomic Medicine: A Narrative Review on CRISPR Technology as a Potential Therapeutic Tool for Human Diseases. *Biomed. Res. Int.* **2019**, *2019*, 1369682.

(626) Seshadri, D. R.; Li, R. T.; Voos, J. E.; Rowbottom, J. R.; Alfes, C. M.; Zorman, C. A.; Drummond, C. K. Wearable Sensors for Monitoring the Physiological and Biochemical Profile of the Athlete. *npj Digit. Med.* **2019**, *2*, 72.

(627) Kwong, G. A.; Ghosh, S.; Gamboa, L.; Patriotis, C.; Srivastava, S.; Bhatia, S. N. Synthetic Biomarkers: A Twenty-First Century Path to Early Cancer Detection. *Nat. Rev. Cancer* **2021**, *21*, 655−668.

(628) Khosravi, S.; Bailey, S. G.; Parvizi, H.; Ghannam, R. Wearable Sensors for Learning Enhancement in Higher Education. *Sensors* **2022**, *22*, 7633.

(629) Zhong, Q.; Tan, E. K. W.; Martin-Alonso, C.; Parisi, T.; Hao, L.; Kirkpatrick, J. D.; Fadel, T.; Fleming, H. E.; Jacks, T.; Bhatia, S. N. Inhalable Point-of-Care Urinary Diagnostic Platform. *Sci. Adv.* **2024**, *10*, eadj9591.

(630) Cohen, J. D.; Li, L.; Wang, Y.; Thoburn, C.; Afsari, B.; Danilova, L.; Douville, C.; Javed, A. A.; Wong, F.; Mattox, A.; Hruban, R. H.; Wolfgang, C. L.; Goggins, M. G.; Dal Molin, M.; Wang, T.-L.; Roden, R.; Klein, A. P.; Ptak, J.; Dobbyn, L.; Schaefer, J.; et al. Detection and Localization of Surgically Resectable Cancers with a Multi-Analyte Blood Test. *Science* **2018**, *359*, 926−930.

(631) Hao, L.; Zhao, R. T.; Welch, N. L.; Tan, E. K. W.; Zhong, Q.; Harzallah, N. S.; Ngambenjawong, C.; Ko, H.; Fleming, H. E.; Sabeti, P. C.; Bhatia, S. N. CRISPR-Cas-Amplified Urinary Biomarkers for Multiplexed and Portable Cancer Diagnostics. *Nat. Nanotechnol.* **2023**, *18*, 798−807.

(632) Wang, C.; Liu, M.; Wang, Z.; Li, S.; Deng, Y.; He, N. Point-of-Care Diagnostics for Infectious Diseases: From Methods to Devices. *Nano Today* **2021**, *37*, 101092.

(633) Narasimhan, V.; Kim, H.; Lee, S. H.; Kang, H.; Siddique, R. H.; Park, H.; Wang, Y. M.; Choo, H.; Kim, Y.; Kumar, S. Nucleic Acid Amplification-Based Technologies (NAAT)—Toward Accessible, Autonomous, and Mobile Diagnostics. *Adv. Mater. Technologies* **2023**, *8*, 2300230.

(634) Sempionatto, J. R.; Lasalde-Ramirez, J. A.; Mahato, K.; Wang, J.; Gao, W. Wearable Chemical Sensors for Biomarker Discovery in the Omics Era. *Nat. Rev. Chem.* **2022**, *6*, 899−915.

(635) Taton, T. A.; Mirkin, C. A.; Letsinger, R. L. Scanometric DNA Array Detection with Nanoparticle Probes. *Science* **2000**, *289*, 1757−1760.

(636) Ji, C.; Wei, J.; Zhang, L.; Hou, X.; Tan, J.; Yuan, Q.; Tan, W. Aptamer-Protein Interactions: From Regulation to Biomolecular Detection. *Chem. Rev.* **2023**, *123*, 12471−12506.

(637) Chinen, A. B.; Guan, C. M.; Ferrer, J. R.; Barnaby, S. N.; Merkel, T. J.; Mirkin, C. A. Nanoparticle Probes for the Detection of Cancer Biomarkers, Cells, and Tissues by Fluorescence. *Chem. Rev.* **2015**, *115*, 10530−10574.

(638) Ramesh, M.; Janani, R.; Deepa, C.; Rajeshkumar, L. Nanotechnology-Enabled Biosensors: A Review of Fundamentals, Design Principles, Materials, and Applications. *Biosensors* **2023**, *13*, 40.

(639) Jin, C.; Wu, Z.; Molinski, J. H.; Zhou, J.; Ren, Y.; Zhang, J. X. J. Plasmonic Nanosensors for Point-of-Care Biomarker Detection. *Mater. Today Bio* **2022**, *14*, 100263.

(640) Soldado, A.; Barrio, L. C.; Diaz-Gonzalez, M.; de la Escosura-Muniz, A.; Costa-Fernandez, J. M. Advances in Quantum Dots as Diagnostic Tools. *Adv. Clin. Chem.* **2022**, *107*, 1−40.

(641) Dincer, C.; Bruch, R.; Kling, A.; Dittrich, P. S.; Urban, G. A. Multiplexed Point-of-Care Testing - xPOCT. *Trends Biotechnol.* **2017**, *35*, 728−742.

(642) Pavia, C. S.; Plummer, M. M. The Evolution of Rapid Antigen Detection Systems and their Application for COVID-19 and Other Serious Respiratory Infectious Diseases. *J. Microbiol. Immunol. Infect.* **2021**, *54*, 776−786.

(643) Newsome, M. We Must Improve Equity in Cancer Screening. *Nature* **2021**, DOI: 10.1038/d41586-021-03403-8.

(644) Thwala, L. N.; Ndlovu, S. C.; Mpofu, K. T.; Lugongolo, M. Y.; Mthunzi-Kufa, P. Nanotechnology-Based Diagnostics for Diseases Prevalent in Developing Countries: Current Advances in Point-of-Care Tests. *Nanomaterials* **2023**, *13*, 1247.

(645) Liu, Y.; Li, Y.; Hang, Y.; Wang, L.; Wang, J.; Bao, N.; Kim, Y.; Jang, H. W. Rapid Assays of SARS-CoV-2 Virus and Noble Biosensors by Nanomaterials. *Nano Converg.* **2024**, *11*, 2.

(646) Chehelgerdi, M.; Chehelgerdi, M.; Allela, O. Q. B.; Pecho, R. D. C.; Jayasankar, N.; Rao, D. P.; Thamaraikani, T.; Vasanthan, M.; Viktor, P.; Lakshmaiya, N.; Saadh, M. J.; Amajd, A.; Abo-Zaid, M. A.; Castillo-Acobo, R. Y.; Ismail, A. H.; Amin, A. H.; Akhavan-Sigari, R. Progressing Nanotechnology to Improve Targeted Cancer Treatment: Overcoming Hurdles in its Clinical Implementation. *Mol. Cancer* **2023**, *22*, 169.

(647) Zhang, Y.; Tian, X.; Wang, Z.; Wang, H.; Liu, F.; Long, Q.; Jiang, S. Advanced Applications of DNA Nanostructures Dominated by DNA Origami in Antitumor Drug Delivery. *Front. Mol. Biosci.* **2023**, *10*, na DOI: 10.3389/fmolb.2023.1239952.

(648) Herbert, F. C.; Abeyrathna, S. S.; Abeyrathna, N. S.; Wijesundara, Y. H.; Brohlin, O. R.; Carraro, F.; Amenitsch, H.; Falcaro, P.; Luzuriaga, M. A.; Durand-Silva, A.; Diwakara, S. D.; Smaldone, R. A.; Meloni, G.; Gassensmith, J. J. Stabilization of Supramolecular Membrane Protein-Lipid Bilayer Assemblies through Immobilization in a Crystalline Exoskeleton. *Nat. Commun.* **2021**, *12*, 2202.

(649) Kumari, S.; Martinez-Garcia, J.; Ehrman, R. N.; Tang, W.; Miles, J.; Basak, P.; Howlett, T. S.; Wijesundara, Y. H.; Wang, Z.; Izzo, A.; Restrepo, B.; Lu, L.; Meloni, G.; Gassensmith, J. J. Testing the Antigenic Potential of Transmembrane Proteins To Develop a Thermostable Tuberculosis MOF-Liposomal Vaccine. *ACS Infect. Dis.* **2025**, *11*, 204−215.

(650) *ACS Approval Program Coursework*. https://www.acs.org/education/policies/acs-approval-program/guidelines/coursework.html#MSNreq (accessed 2024 November 9).

(651) *UAB Bachelor's Degree in Nanoscience and Nanotechnology*. https://www.uab.cat/web/estudiar/ehea-degrees/general-information-1216708259085.html?param1=1345879691832 (accessed 2025 March 13).

(652) *Facultade de Ciencias Nanoscience and Nanotechnology*. https://ciencias.udc.es/en/degree-in-nanoscience-and-nanotechnology (accessed 2025 March 13).

(653) Jackman, J. A.; Cho, D.-J.; Lee, J.; Chen, J. M.; Besenbacher, F.; Bonnell, D. A.; Hersam, M. C.; Weiss, P. S.; Cho, N.-J.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968

Nanotechnology Education for the Global World: Training the Leaders of Tomorrow. *ACS Nano* **2016**, *10*, 5595−5599.
(654) Malsch, I. Nano-Education from a European Perspective: Nano-Training for Non-R&D jobs. *Nanotechnology Reviews* **2014**, *3*, 211−221.
(655) *National Nanotechnology Initiative's Strategic Plans*. https://www.nano.gov/strategicplans (accessed 2024 November 9).
(656) Bhushan, B. Introduction to Nanotechnology: History, Status, and Importance of Nanoscience and Nanotechnology Education. In *Global Perspectives of Nanoscience and Engineering Education*; Winkelmann, K.; Bhushan, B., Eds.; Springer International Publishing, 2016; pp 1−31.
(657) *Nanooze*. https://nnci.net/nanooze (accessed 2025 March 13).
(658) *National Nanotechnology Initiative, Educational Resources for K-12 Students*. https://www.nano.gov/education-training/k12 (accessed 2025 March 13).
(659) Ashcroft, J. M.; Cakmak, A. O.; Blatti, J.; Bautista, E.; Wolf, V.; Monge, F.; Davis, D.; Arellano-Jimenez, M. J.; Tsui, R.; Hill, R.; Klejna, A.; Smith, J. S.; Glass, G.; Suchomski, T.; Schroeder, K. J.; Ehrmann, R. K. It's RAINing: Remotely Accessible Instruments in Nanotechnology to Promote Student Success. *Curr. Issues Emerg. Elearn.* **2017**, *4*.
(660) *NACK Resource Center*. https://www.cneu.psu.edu/nano4me/ (accessed 2025 March 13).
(661) *UC Santa Barbara Partners with SB City College to Expand Workforce Training in Micro/Nanotechnology and Semiconductor Manufacturing*. https://news.ucsb.edu/in-focus/uc-santa-barbara-partners-sb-city-college-expand-workforce-training-micronanotechnology#:~:text=UC%20Santa%20Barbara%20and%20Santa,tech%20industry (accessed 2025 March 13).
(662) Keller, A. A.; Ehrens, A.; Zheng, Y.; Nowack, B. Developing Trends in Nanomaterials and their Environmental Implications. *Nat. Nanotechnol.* **2023**, *18*, 834−837.
(663) Marrows, C. H.; Barker, J.; Moore, T. A.; Moorsom, T. Neuromorphic Computing with Spintronics. *npj Spintronics* **2024**, *2*, 12.
(664) Saha, M. Nanomedicine: Promising Tiny Machine for the Healthcare in Future-A Review. *Oman Med. J.* **2009**, *24*, 242−247.
(665) Snow, J.; Giordano, J. Aerosolized Nanobots: Parsing Fact from Fiction for Health Security-A Dialectical View. *Health Secur.* **2019**, *17*, 77−79.
(666) van der Meel, R.; Sulheim, E.; Shi, Y.; Kiessling, F.; Mulder, W. J. M.; Lammers, T. Smart Cancer Nanomedicine. *Nat. Nanotechnol.* **2019**, *14*, 1007−1017.
(667) Balusamy, B.; Dhanaraj, R. K.; Seetharaman, T.; Sharma, V.; Shankar, A.; Viriyasitavat, W. Design Control and Management of Intelligent and Autonomous Nanorobots with Artificial Intelligence for Prevention and Monitoring of Blood Related Diseases. *Eng. Appl. Artif. Intell.* **2024**, *131*, 107798.
(668) *Nanotechnology and Patents*. https://www.wipo.int/patent-law/en/developments/nanotechnology.html (accessed 2024 November 5).
(669) *Nanotechnology Under the Magnifying Lens from a European and U.S. Perspective: General Patent Statistics, Non-Obviousness Versus Inventive Step, and Two Case Studies in CNT Commercialization*. https://law.stanford.edu/publications/nanotechnology-under-the-magnifying-lens-from-a-european-and-u-s-perspective-general-patent-statistics-non-obviousness-versus-inventive-step-and-two-case-studies-in-cnt-commercialization/ (accessed 2024 November 5).
(670) Pokrajac, L.; Abbas, A.; Chrzanowski, W.; Dias, G. M.; Eggleton, B. J.; Maguire, S.; Maine, E.; Malloy, T.; Nathwani, J.; Nazar, L.; Sips, A.; Sone, J. i.; van den Berg, A.; Weiss, P. S.; Mitra, S. Nanotechnology for a Sustainable Future: Addressing Global Challenges with the International Network4Sustainable Nanotechnology. *ACS Nano* **2021**, *15*, 18608−18623.
(671) Malik, S.; Muhammad, K.; Waheed, Y. Nanotechnology: A Revolution in Modern Industry. *MOL* **2023**, *28*, 661.
(672) Hansen, S. F.; Baun, A. European Regulation Affecting Nanomaterials - Review of Limitations and Future Recommendations. *Dose Response* **2012**, *10*, 364−383.
(673) Miernicki, M.; Hofmann, T.; Eisenberger, I.; von der Kammer, F.; Praetorius, A. Legal and Practical Challenges in Classifying Nanomaterials According to Regulatory Definitions. *Nat. Nanotechnol.* **2019**, *14*, 208−216.
(674) Chávez-Hernández, J. A.; Velarde-Salcedo, A. J.; Navarro-Tovar, G.; Gonzalez, C. Safe Nanomaterials: From their Use, Application, and Disposal to Regulations. *Nanoscale Adv.* **2024**, *6*, 1583−1610.
(675) Allan, J.; Belz, S.; Hoeveler, A.; Hugas, M.; Okuda, H.; Patri, A.; Rauscher, H.; Silva, P.; Slikker, W.; Sokull-Kluettgen, B.; Tong, W.; Anklam, E. Regulatory Landscape of Nanotechnology and Nanoplastics from a Global Perspective. *Regul. Toxicol. Pharmacol.* **2021**, *122*, 104885.
(676) Snir, R.; Ravid, G. Global Nanotechnology Regulatory Governance from a Network Analysis Perspective. *Regul. Gov.* **2016**, *10*, 314−334.
(677) *JRC Nanomaterials Repository*. https://joint-research-centre.ec.europa.eu/scientific-tools-and-databases/jrc-nanomaterials-repository_en (accessed 2024 November 5).
(678) *OECD: Nanomaterials and Advanced Materials*. https://www.oecd.org/en/topics/nanomaterials-and-advanced-materials.html (accessed 2024 November 5).
(679) *ECHA: European Chemicals Agency*. https://echa.europa.eu/regulations/nanomaterials. (accessed 2024 November 5).
(680) *StatNano*. https://statnano.com (accessed 2024 November 5).
(681) Ali, F.; Neha, K.; Parveen, S. Current Regulatory Landscape of Nanomaterials and Nanomedicines: A Global Perspective. *J. Drug Delivery Sci. Technol.* **2023**, *80*, 104118.
(682) Fadeel, B.; Bussy, C.; Merino, S.; Vázquez, E.; Flahaut, E.; Mouchet, F.; Evariste, L.; Gauthier, L.; Koivisto, A. J.; Vogel, U.; Martín, C.; Delogu, L. G.; Buerki-Thurnherr, T.; Wick, P.; Beloin-Saint-Pierre, D.; Hischier, R.; Pelin, M.; Candotto Carniel, F.; Tretiach, M.; Cesca, F.; et al. Safety Assessment of Graphene-Based Materials: Focus on Human Health and the Environment. *ACS Nano* **2018**, *12*, 10582−10620.
(683) Khan, I.; Saeed, K.; Khan, I. Nanoparticles: Properties, Applications and Toxicities. *Arab. J. Chem.* **2019**, *12*, 908−931.
(684) Shahzad, K.; Mardare, A. I.; Hassel, A. W. Accelerating Materials Discovery: Combinatorial Synthesis, High-Throughput Characterization, and Computational Advances. *Sci. Technol. Adv. Mater.: Methods* **2024**, *4*, 2292486.
(685) Kalinin, S. V.; Sumpter, B. G.; Archibald, R. K. Big-Deep-Smart Data in Imaging for Guiding Materials Design. *Nat. Mater.* **2015**, *14*, 973−980.
(686) Choudhary, K.; DeCost, B.; Chen, C.; Jain, A.; Tavazza, F.; Cohn, R.; Park, C. W.; Choudhary, A.; Agrawal, A.; Billinge, S. J. L.; Holm, E.; Ong, S. P.; Wolverton, C. Recent Advances and Applications of Deep Learning Methods in Materials Science. *npj Comput. Mater.* **2022**, *8*, 59.
(687) Sommer, T.; Willa, R.; Schmalian, J.; Friederich, P. 3DSC - A Dataset of Superconductors Including Crystal Structures. *Sci. Data* **2023**, *10*, 816.
(688) Wilkinson, M. D.; Dumontier, M.; Aalbersberg, I. J.; Appleton, G.; Axton, M.; Baak, A.; Blomberg, N.; Boiten, J.-W.; da Silva Santos, L. B.; Bourne, P. E.; Bouwman, J.; Brookes, A. J.; Clark, T.; Crosas, M.; Dillo, I.; Dumon, O.; Edmunds, S.; Evelo, C. T.; Finkers, R.; Gonzalez-Beltran, A.; et al. The FAIR Guiding Principles for Scientific Data Management and Stewardship. *Sci. Data* **2016**, *3*, 160018.

https://doi.org/10.1021/acsnano.5c12854
ACS Nano 2025, 19, 31933−31968