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Editorial

The Next 25 Years of Nanoscience and Nanotechnology: A *Nano Letters* Roadmap

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2025 marks the 25th anniversary of *Nano Letters*, and to celebrate this milestone, our editorial team has put together a Roadmap for the next 25 years. Nanoscience and nanotechnology have come a long way since the first journals dedicated exclusively to nanoscale concepts were founded. In this prospective piece, we have identified 7 macroscale themes broken down into 16 key topical areas and speculated about their strategic, developmental, and translational milestones. We have tried to be specific and quantitative regarding examples highlighted without being overly prescriptive. We have also done our best to propose big-picture and high-risk breakthroughs that will require integrated disciplinary expertise, significant resource investments, and decades-long time horizons for realization. We hope that you are as optimistic and excited about the future of nanoscience as we are and that this Roadmap can be an aspirational and functional guidepost for our community.

1. NANOELECTRONICS

Nanoelectronics

Mid-level Theme	Sub-Topics	2025 Strategic Milestones 0-5 years	2030 Developmental Milestones 5-10 years	2035 Transformative Milestones 10-25 years (2050)
Nanoelectronics and Advanced Computing	• 2D Semiconductors • CNT channels • TFETs & non-thermionic switching • Ferroelectric/ferromagnetic devices • 3D monolithic integration	Achieve wafer-scale 2D/CNT transistors with clean vdWs controlled doping, and BEOL thermal stability (≤ 400 °C).	Demonstrate MoS_2 n-FETs and WSe_2 p-FETs with negative-capacitance gates and spin-orbit-torque MRAM in the pJ–fJ energy range.	Deliver exascale-class computing within smartphone-level power through advanced layer-stacking and close industry–academia collaboration.
vdW Heterostructures and Low-dimensional Integration	• 2D growth • Twist control • Defect engineering • Moiré assembly • Process integration	Scale MOCVD/CVD of high-quality 2D semiconductors to 200 mm wafers with <1% defect density and sub-degree twist uniformity.	Realize deterministic full-wafer stacking of moiré superlattices with preprogrammed quantum phases.	Operate mixed-dimensional foundry lines that seamlessly incorporate vdW stacks, bulk CMOS, and photonic layers at production scale.
Quantum Materials and Information Platforms	• Superconducting qubit arrays • Semiconductor qubits • Error correction • 2D quantum materials • Quantum sensors	Deploy scalable error-correction schemes to suppress decoherence and expand superconducting qubit arrays.	Integrate on-chip interconnects and cryogenic microelectronics to link and control large semiconductor-qubit registers.	Harness 2D moiré materials for topologically protected qubits and field-ready quantum sensors (NV centers and SiC defects) across applications.

1.1. Nanoelectronics and Advanced Computing. The two approaches that have been pursued in the design of next-generation electronic devices have focused on post-Si nanoelectronics and beyond CMOS nanoelectronics. For the former, post-Si nanoelectronics leverages channel materials such as two-dimensional (2D) semiconductors and carbon nanotubes (CNTs) and aims to extend CMOS scaling toward the 1 nm technology node (and below) while maintaining compatibility with conventional device architectures. These materials offer improved electrostatics and scalability, enabling continued progress along Moore's Law within the CMOS framework. For the latter, beyond-CMOS nanoelectronics includes cold-

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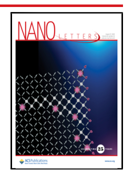

source injection, tunneling field-effect transistors (TFETs), other nonthermionic switching mechanisms, and ferroelectric and ferromagnetic materials for both logic and memories. This approach aims to overcome the thermodynamic limits of today's transistors or in-memory-computation devices, which are constrained to ∼0.7 V operation and ∼65−70 mV/decade subthreshold swings. By introducing fundamentally new device physics, beyond-CMOS technologies promise subthermal-limit operation essential for sustainable, large-scale deployment in next-generation Internet of Things (IoT) and edge computing artificial intelligence (AI) systems. Drastic reductions in the power consumption of computing devices are highly desirable, as current projections suggest that energy constraints will limit data centers and AI deployment within the next five years.

The critical challenge for 2D and CNT technologies lies in realizing manufacturable channel transistors with pristine van der Waals interfaces, controlled doping profiles, and scalability to wafer-level integration—all while maintaining thermal stability under ≤400 °C back-end-of-line (BEOL) conditions. Current 2D semiconductors exhibit relatively high interfacial trap densities (∼10^{12} cm^{-2}) compared to Si/SiO_2 (∼10^{10} cm^{-2}), which limits their subthreshold performance and interface reliability. TFETs face persistent challenges, including low on-state currents due to limited tunneling efficiency, sensitivity to doping and interface abruptness, and stringent material requirements for steep band-to-band tunneling junctions. Cold-source injection FETs similarly have difficulties in engineering sharp injection profiles and maintaining low-resistance contacts, particularly under BEOL-compatible thermal budgets.

Looking forward, we imagine million-transistor monolithic 3D heterogeneous integration by 2030 and 2D transistors (e.g., MoS_2 n-FETs and WSe_2 p-FETs) with oxide- or wurtzite-nitride-based ferroelectric negative-capacitance gates. Spin−orbit torque MRAM may enable ultralow-energy logic and memory operations in the pJ−fJ range by 2035. At the architecture level, emerging paradigms such as nonvolatile in-memory computing and neuromorphic systems will rely on dense, stable, and energy-efficient memory technologies. These advances are crucial for transformative applications, from autonomous vehicles requiring real-time sensor fusion at subwatt powers to self-powered health monitoring biosensors and distributed AI inference in edge computing. Ubiquitous subthreshold computing may unlock entirely new capabilities in real-time sensing and anomaly detection. Achieving this vision will require sustained foundry-level investment in new materials, innovation across atomic-layer growth and transfer methods for stacked nanosheet devices, and close industry−academia partnerships—paving the way toward exascale computing within smartphone power budgets and redefining the semiconductor landscape.

1.2. vdW Heterostructures and Low-Dimensional Integration. Over the next quarter century, 2D materials systems like van der Waals (vdW) heterostructures will redefine how we build multifunctional electronics and photonics. Stacking dissimilar 2D crystals like Legos—precisely controlling twist angle, layer order, and defect landscape—will enable both engineering of molecular-scale electronics with layer-by-layer control, as well as designer band structures through interlayer coupling between disparate materials or via moiré superlattices. One overarching challenge is that the same atomic-scale features and strong coupling that result in desirable properties also make 2D materials far more sensitive to disorder and their environment than thin-film electronics. Since the widespread introduction of exfoliated graphene over 20 years ago, vdW-bonded materials have dominated materials research. With building blocks including metals, direct and indirect gap semiconductors, insulators, magnetically ordered materials, superconductors, and more, the palette of materials available for stacking, with or without interlayer twists, is vast. At present, scalable creation of designer heterostructures is extremely difficult, with the highest-quality 2D materials still from the exfoliation of bulk crystals, and therefore far smaller than wafer scales. Although exciting properties or superlative performance have been demonstrated at the single-device level, questions for the next years include how to manufacture systems at technologically relevant scales and how to integrate 2D materials (and other lower-dimensional materials) with thin-film CMOS processes.

Just as Si electronics were a prerequisite for MEMS and photonics industries, we expect that the first widespread application of 2D materials will be in the semiconductor industry. Currently, semiconductor industry roadmaps are proposing 2D semiconductors like MoS_2 or WSe_2 to replace Si as the channel material in 2035. In the near term (0−5 years), the focus will be on scaling MOCVD/CVD growth of high-quality 2D semiconductors to 200 mm wafers, achieving <1% defect densities while maintaining subdegree twist uniformity, and developing transfer processes to integrate the materials into existing architectures without introducing new disorder. Once these initial manufacturing challenges have been resolved, we anticipate that 2D heterostructures will be adopted by other technologies that either require disparate capabilities or need more stringent control over quality. By the mid-2030s (5−10 years), we expect that deterministic, full-wafer assembly of moiré superlattices, whose electronic phases, such as superconductivity, excitonic insulation, or topological order, can be programmed *a priori*. This capability can seed "twistronic" devices, in which programmable quantum matter can coexist with classical circuitry on the same die. Looking further ahead (10−25 years), heterogeneous 2D/3D foundry lines may routinely integrate vdW stacks, bulk CMOS, and photonic layers, such that mixed-dimensional logic, photonic, and sensing chips can be manufactured at scale. Such platforms will facilitate data compression, reduce energy needed per operation, and enable bespoke system-on-chip solutions for everything from neuromorphic AI to quantum interconnects, cementing vdW heterostructures as a cornerstone of next-generation electronics.

1.3. Quantum Materials and Information Platforms. The next technological revolution will be driven by quantum information science and technology (QIST). Quantum computing and quantum sensing operate on the principles of entanglement and coherence. Overcoming the challenges of decoherence, the development of error correction schemes, and the scaleup and integration with existing technologies are key challenges that require continuous materials innovations and engineering at all levels. The most advanced solid-state quantum computation platform in 2025, which has arguably demonstrated a quantum advantage over classical counterparts in solving certain classes of problems, consists of arrays of ∼1000 superconducting qubits. However, these superconducting qubits have very large footprints (∼mm^2) and require ultralow operating temperatures and complex error correction schemes; hence, scaling up beyond the current state of the art is challenging. In parallel, semiconductor qubit platforms are rapidly advancing beyond the current few-qubit level. For

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practical use, each platform needs to develop effective on-chip interconnects and cryogenic microelectronics and to manage information flow at the quantum−classical interface. These challenges call for innovations and sustained development in materials, circuitry, and quantum algorithms. Nontraditional, 2D electronic material platforms with atomically sharp and crystalline interfaces may offer alternative solutions. Recent advances in 2D moiré materials have uncovered emergent electronic phases such as superconductivity with unconventional pairing, (anti)ferromagnetism, nematicity, and integer and fractional quantum anomalous Hall effects. Often, these phases can exist in the same material and can be accessed in situ via tuning of carrier density or external fields. Not only is new physics from topology and quantum geometry exciting, but also their understanding can help enable technologies such as topologically protected qubits.

In addition, quantum sensors offer promising avenues to boost the sensitivity and spatial resolution of magnetic field detection, which will have an impact on diverse applications, including navigation and biomedical imaging. Sensors based on nitrogen-vacancy (NV) centers in diamond are rapidly moving into commercialization. Defect centers in SiC boast long coherence times and compatibility with the semiconducting industry, and planar platforms such as single-defect emitters in hexagonal boron nitride and other vdW compounds can be readily integrated with other 2D materials. QIST, enabled by quantum materials, has the potential to accelerate and revolutionize information processing and storage, AI, and communications. Over the next decades, we believe that the discovery and optimization of novel materials and their associated phenomena will be foundational for disruptive paradigms and technologies.

2. NANOPHOTONICS

Nanophotonics

Mid-level Theme	Sub-Topics	2025 Strategic Milestones 0-5 years 2030	Developmental Milestones 5-10 years 2035	Transformative Milestones 10-25 years 2050
Engineering Light-matter Interactions	• Weak coupling • Strong coupling & polaritons • Ultrafast nonequilibrium • Photocatalysis & synthesis • Optical cavities & interconnects	Deliver advances in nanoscale light–matter interactions that enable fundamental investigations at extreme spatial and temporal resolutions.	Realize ambient-condition control of light–matter interactions with minimal GHG emissions, leveraging optical cavities and ultrafast nonequilibrium dynamics.	Establish large-scale light-driven synthesis for sustainable industry and energy-efficient interconnects for low-power AI and quantum networking.
Nano-optical Devices	• Nanolasers & switches • Modulators & detectors • Quantum emitters • Emitter–cavity placement • Metasurfaces & 3D self-assembly	Establish advanced fabrication for precise placement of high-quality quantum emitters in photonic cavities.	Develop new materials and approaches for nanophotonic integrated circuits to enable monolithic integration of photonics and optoelectronics.	Deliver photonic logic gates and quantum simulation and quantum-computing architectures.

2.1. Engineering Light−Matter Interactions. Light−matter interactions govern phenomena ranging from photosynthesis to photovoltaics (PVs) to optical microscopy to photonic communications. Harnessing such interactions at the nanoscale not only enables fundamental investigations into nanomaterials at extreme spatial and temporal resolutions but also provides the foundation for numerous technologies spanning energy generation and storage, chemical synthesis, and biomedicine.

Distinct interaction regimes of light and matter include weak and strong coupling. In the weak-coupling regime, the coupling rate between matter and photons in a cavity is less than the decay rate of the system. Here, we envision applications that include molecular sensing and sequencing (including chiral-optical structures), photochemistry and catalysis, and optoelectronic devices. In the strong-coupling regime, energy is exchanged between matter and the cavity field before dissipation. This regime can result in new classes of quasiparticles that exhibit macroscopic quantum properties (e.g., Bose−Einstein condensation, superfluidity, or supersolidity), as well as dynamic propagation of carriers (e.g., phonon polaritons, plasmon polaritons, exciton polaritons). In the near term (0−5 years), we project considerable advances in light−matter interactions that enable dynamic probing of single molecules and single cells; excited-state photocatalysis for high-yield, selective catalysis of high-value chemicals; and materials that can control the coupling between light, heat, and electrons for energy generation and storage. By the mid-2030s (5−10 years), we project that controlling light−matter interactions can enable photo-(electro)catalysis of high-value chemicals under ambient conditions and with minimal greenhouse gas (GHG) emissions, unusual fields of "omics" (e.g., metabolomics, lipidomics, proteomics) enabled by optical cavities, and advanced components for thermal management resulting from ultrafast (subps to ns) and nonequilibrium dynamics. In the longer term (10−25 years), we envision the use of large-scale photoreactors for sustainable industrial molecular synthesis, light-driven synthesis of whole genomes for synthetic biology, and Tbs/W interconnects for low-power AI and quantum networking.

2.2. Nano-Optical Devices. The knowledge gained from engineering light−matter interactions will provide a foundation for advanced nanophotonic devices, including optically and electrically pumped nanolasers, switches, modulators, and photodetectors. A driving motivation is industry demand for monolithic integration of photonics and optoelectronics and ultimately for all-optical interconnects in microelectronics, photonic logic gates, and quantum networks. Realizing next-

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generation photonic systems will require advanced fabrication methods for the precise placement of emitters into photonic cavities. High-quality quantum emitters include semiconducting quantum dots, a wide range of atomic defects in 2D semiconducting and dielectric materials, and moiré superlattices. Such emitters can be combined with a wide range of photonic structures, such as microcavities, waveguides, and metasurfaces. We envision that high-quality, on-demand quantum emitters and future monolithic chips with indistinguishable emitters are possible within the next 5−10 years.

The development of nanomaterials that can combine Si-based microelectronics platforms with superior photonic ones toward integrated nanophotonics and optoelectronics remains critical. Recent progress includes III−V materials on Si/SiGe for on-chip light sources and modulators, lithium niobate on Si for electro-optic conversion, and 2D materials heterointegration for ultrathin emitters and detectors. Nonetheless, the challenges of heterogeneous integration are far from solved given the intertwined problems of mechanical and thermal stability, suboptimal external quantum efficiencies, and poor coupling efficiency and limited tunability. In the next 5−10 years, we envision new materials and approaches for nanophotonic integrated circuits. For example, designs based on stacked metasurfaces or concepts from 3D self-assembly and DNA-origami can be used for efficient routing toward on-chip and unconventional 3D integrated photonic circuits, topological concepts can be exploited for manipulating light propagation without adverse effects from disorder, and strong or ultrastrong light−matter interactions involving hybrid quasiparticles for tuning nonlinear interactions that are absent in photons alone. Longer term, we anticipate that these advances could result in photonic logic gates and quantum simulation and quantum computing architectures (e.g., neuromorphic computing, Ising- or XY-type quantum simulators).

3. NANO BIO

Nano Bio

Mid-level Theme	Sub-Topics	2025 Strategic Milestones 0-5 years 2030	Developmental Milestones 5-10 years 2035	Transformative Milestones 10-25 years 2050
Soft, Flexible and Wearable Electronics	• Soft sensing • Flexible circuits • Biosensor integration • Energy autonomy • Ambient intelligence	Develop nanotechnology-enabled soft materials that both sense and compute with mechanical moduli below 1 MPa and balanced electronic–mechanical performance.	Deploy adaptive wearable systems with pervasive sensing and computation that operate energy-autonomously via integrated nanomaterials.	Achieve seamless integration of soft, flexible electronics with bodies and environments to deliver ubiquitous ambient intelligence and extend human perception.
Bio-Inspired and Living Nanomaterials	• Hierarchical design • Self-assembly • Biointerfaces • Chemical encoding • Systems integration	Perfect peptide- and DNA-guided nanoparticle assembly with dynamic self-organization and cell-laden hydrogel interfaces.	Enable entropy-driven assembly encoded with chemical cues to create autonomous, reconfigurable nanosystems for real-time diagnostics.	Merge synthetic nanostructures and living matter into brain–machine interfaces, neuroregenerative devices, and anti-aging therapies.
Nanorobotics and Active Matter	• Self-propulsion • External actuation • Biomedical sensing • Navigation control • Component assembly	Achieve untethered guidance of micro/nano-robots through complex, heterogeneous biological fluids.	Fabricate nano-robots with tailored surface anchors and strain-engineered domains to enable biocompatible propulsion.	Deploy autonomous, energy-harvesting nano-robots that perform cellular-level repairs, halving patient recovery times.

3.1. Soft, Flexible, and Wearable Electronics. Since the first proposed computational devices, there has been a race to invent and realize computing platforms with increasingly compact form factors based on new materials, architectures, and prospects for biointegration. Today, a supercomputer can be worn on our wrists for health monitoring or even implanted into our brains for overcoming paralysis, but rigid substrates are highly limiting. The rapid evolution of new form factors requiring soft and flexible designs continues to generate and redefine applications.

By evolving the materials that can intelligently sense, compute, and react, wearable electronics are dramatically changing how humans interact with our environment. Moreover, soft materials are inherently robust with mechanical moduli below 1 MPa. However, a major challenge is balancing simultaneously electronic and mechanical performance. Nanotechnology will remain the core enabler of this transformation by providing the foundational materials, precision fabrication capabilities, and advanced functions to realize pervasive sensing and adaptive systems that could even be energy autonomous. By 2050, we anticipate that soft, flexible, and wearable electronics, shaped by sustained advances in nanotechnology, will transition from scientific and technical curiosities to ubiquitous and indispensable components of daily life—seamlessly integrating with our bodies and environments to extend human capabilities and perception. We anticipate that the future will be one of pervasive ambient intelligence, where computing can be integrated on or inside our bodies because of systematic gains in soft flexible electronics.

3.2. Bio-Inspired and Living Nanomaterials. Over the next 25 years, bio-inspired and living nanomaterials will transform how humans interact with biological systems.

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Materials inspired by the hierarchical complexity of nature will be able to adapt, evolve, and communicate across molecular, cellular, and systemic levels. Such materials hold the key to breakthroughs in sensing, disease intervention, and tissue regeneration. Today's leading systems range from peptide- or DNA-directed nanoparticle synthesis and dynamic self-assembly to hybrid biointerfaces such as hydrogels containing cells, electrochemically responsive scaffolds, and smart drug delivery vehicles with spatiotemporal control. These advances demonstrate how synthetic and biological elements can be bridged; however, there are still limitations in autonomous function, adaptive precision, and systemic integration. One key challenge is reliable interfacial control between synthetic nanomaterials and living systems, with the biggest obstacle being the integration of atomic-level functional diversity with biological specificity. For example, how can we engineer nanoparticles with atomic precision that can also operate harmoniously within the stochastic, entropic, and dynamic environments of tissues and organs?

A transformative approach involves mastering entropy-guided self-assembly and chemical information encoding so that nanoscale building blocks can form adaptive, reconfigurable systems autonomously. The future requires more than just molecular design—a systems-level understanding that incorporates tissue mechanics, metabolic feedback loops, and the coordination of complex chemical networks is critical. There are numerous opportunities for developing versatile platforms that integrate synthetic nanostructures with dynamic biological environments, which can facilitate real-time diagnostics, programmable microenvironments, and precisely targeted therapies. Moving beyond mere structural imitation, the next frontier is to decode how information and energy flow govern biological efficiency and decision making. Nanoscale tools will play a crucial role in probing and controlling these flows, and for ultimately paving the way for brain−machine interfaces, neuroregenerative strategies, and antiaging therapeutics. Achieving this vision will require close collaborations across nanotechnology, synthetic biology, neuroscience, and systems engineering—uniting fields so that in the future living matter is no longer passive but actively programmed to heal, sense, and evolve alongside us.

3.3. Nanorobotics and Active Matter. Micro/nanorobots and active matter are positioned to become essential tools for precise diagnostics, targeted treatments, and cellular-level surgery, which will ultimately enhance the quality of life. Nanorobots can move either by self-propulsion or by activation via external stimuli. To date, they have primarily been used in biomedicine (in vitro trials under conditions mimicking in vivo models and in vivo trials on animal models), where they can locally administer chemicals (active ingredients or drugs) or function as localized sensors to monitor rheological properties that can be correlated to a specific medical condition. The single most formidable technical barrier to progress is achieving precise, untethered control and navigation within dynamic, heterogeneous biological environments. This environment is inherently challenging due to the pervasive influence of Brownian motion in biological fluids with different viscosities, the need for real-time tracking at the nanoscale, and constant attacks by the immune system.

Since each organ in the body is distinct, different types of robots have been developed for efficacy; for example, the microenvironment and rheology of the lungs are very different from those of the skin or the bladder. Currently, most robots are propelled by acoustic or magnetic fields, but these stimuli are difficult to sustain in the body for extended periods of time, and penetration depths are limited. Other approaches involve chemical or enzymatic propulsion, but there are issues of toxicity and harm to the biological environment. General issues include designing nanorobots with materials that are nontoxic and biodegradable and the ability to steer them. We expect that building of designer nanoscale components, such as using nanoparticles with controlled shapes and sizes and with well-defined locations on their surfaces where molecular components can be anchored, can address the former and that precisely connected and purposely shaped subdomains to improve the hydrodynamics of propulsion can inform the latter. Such advances may transform and minimize invasive procedures in specific organs and result in highly personalized medicine through targeted drug delivery.

By 2050, we anticipate that self-powered nanorobots will be capable of performing cellular-level interventions for tissue repair and genetic correction and reducing recovery times by at least 50% compared to current macroscopic methods. In addition, advanced human−machine interfaces like brain−computer interfaces for neurological disorders might be possible. However, associated with these milestones, there are significant regulatory hurdles, as well as ethical concerns regarding data privacy, human identity, and equitable access. Hence, a proactive "safe-by-design" approach to nanomaterial development and regulatory frameworks will be needed. Also, we propose that sustained interdisciplinary research, significant resources in scalable additive nanomanufacturing, and expertise spanning materials chemistry, mechanics, and advanced fabrication are required to achieve unprecedented capabilities in health and human augmentation.

4. NANO ENVIRONMENT

4.1. Environmental Nano and Circular Economy. There is an urgent public health crisis driven by increasing exposure to harmful chemicals such as perfluoroalkyls in drinking water, microplastics in the soil and water, and volatile organic compounds in the air. Addressing this need requires focused efforts on developing manufacturing processes that consider and integrate circular-economy factors so that we can reduce the environmental burden of the materials and devices that we have come to depend on. For example, new catalysts could accelerate the conversion of pollutants to usable products. However, what is lacking is the development of efficient methods to produce advanced nanomaterials through recycling that can lead to improved environmental, social, and regulatory outcomes.

Closing this synthetic loop from pollutants to usable materials requires not only mechanistic insight into chemical transformations but also scalable production, standardized testing and field deployment of remediation nanomaterials, and robust disposal and recycling pathways. Large-scale fabrication of designer antifouling membranes for water purification and desalination is also important via nanoscale interface engineering. Over the next 5−15 years, breakthroughs in the translation of high-quality syntheses of nanomaterials from lab to pilot scale production, in operando characterization of nanomaterials across length scales, and the use of computational tools for prediction, as well as characterization will enable the translation of new discoveries into adoptable solutions. Key advances will pave the way for cleaner effects on the environment, as well as better manufacturing of chemicals and materials. To realize these milestones, collaborative efforts across disciplines, among

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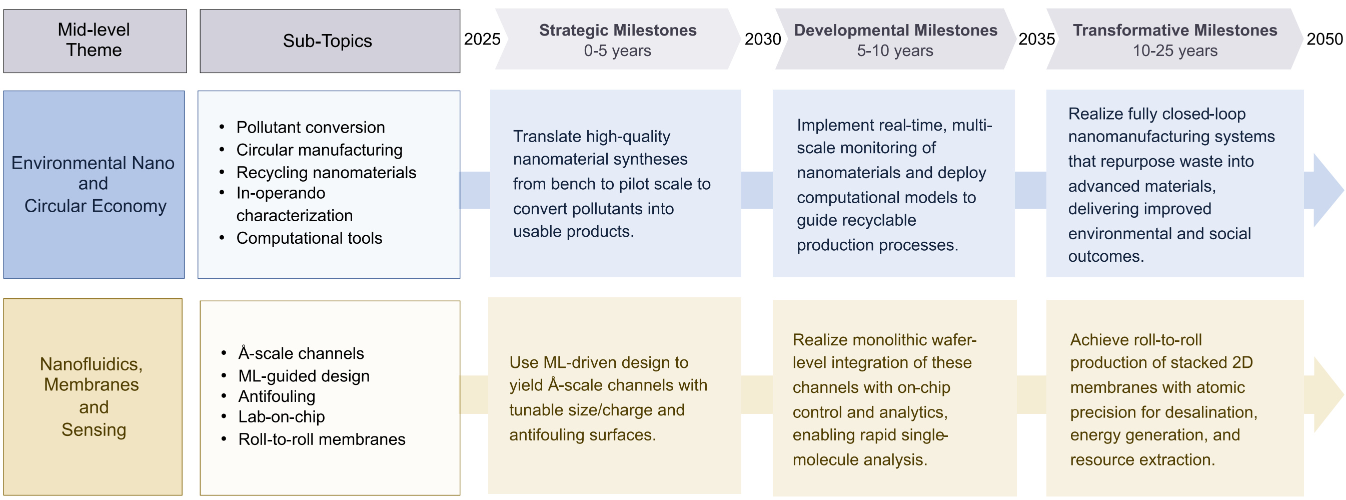
academic institutions, national laboratories, and start-up and established industries, and across national borders, will be essential.

4.2. Nanofluidics, Membranes, and Sensing. Ångstrom-scale nanochannels are poised to turn molecular transport into a programmable design feature, enabling a single platform to desalinate seawater, harvest salinity-gradient energy sources ("blue energy"), reclaim lithium from industrial brines, and read single DNA bases in real time. Laboratory devices have already achieved Li^+:Na^+ selectivity above 10^3 at <3 bar, but they have been limited to mm-scale chips and also lose a third of their performance after only weeks in real fluids. Fragile pore chemistries and rapid biofouling remain major roadblocks. The manufacture of centimeter- to meter-scale membranes that can preserve atomic-level precision and maintain antifouling coatings is a grand challenge because even one defect or biofilm nucleation site can collapse both selectivity and flux.

Nano Environment



Over the next five years, we anticipate that machine-learning-guided molecular dynamics will direct the synthesis of densely packed ($\geq 10^{12}$ pores/cm^2) channels whose diameter and surface charge can be tuned like electronic bandgaps. By the mid-2030s, those channels can be monolithically integrated on 300 mm wafers with electro-osmotic pumps, thin-film electrodes, and edge-AI classifiers, which would produce palm-sized "lab-on-a-chip" cartridges that can analyze single molecules in under 60 s from <5 μL samples. Looking toward 2045, roll-to-roll lines may mass produce meter-scale 2D heterogeneously stacked membranes that can desalinate, harvest $\geq$15 W/m^2 blue energy, and recover >80% lithium in one pass at <\$0.25/m^3 water cost. To ensure equitable access, open performance benchmarks and humanitarian licensing must accompany these advances. Coordinated investment across materials science, CMOS foundries, water utilities, and AI analytics will transform nanofluidics from a laboratory curiosity into the backbone of a circular, water–energy–materials economy by midcentury.

5. NANO ENERGY

5.1. Sustainable Energy and Electrocatalysis. The rapid global increase in energy and materials demand, coupled with mounting environmental pressures, underscores the critical importance of sustainable energy and electrocatalysis over the next quarter century. Despite interest and progress in recent decades—including the emergence of gigawatt-scale batteries and electrolyzer manufacturing capabilities—there remains a significant gap before these technologies can meaningfully displace conventional, fossil fuel-based systems at scale. One of the primary challenges lies in both the high cost and limited availability of critical materials, such as noble metals used in electrolyzers, resource-limited metals in lithium-ion batteries, and rare-earth metals in magnets and catalysts. These factors contribute to the relatively high cost of renewable energy and catalysis-based products, rendering them less competitive than their established fossil-fuel counterparts. Although promising alternative materials have been identified, their widespread adoption remains limited due to the slow pace of exploratory synthesis, incomplete mechanistic understanding, and issues in scaling and processing.

Advances in nanotechnology are poised to accelerate cost reduction and performance improvements. Breakthroughs in in situ/operando nanoscale characterization, atomically precise synthesis of nanomaterials, and computational tools integrated with AI offer potential to deepen our understanding and accelerate the discovery of next-generation materials in energy and sustainability applications. Such progress could reduce costs by another two to three times over the next 25 years, enabling true competition with conventional energy technologies. These material developments will fundamentally reshape the way we produce, transport, and consume energy, as well as how we manufacture chemicals and materials. Looking ahead, collaborative efforts across disciplines, combined with international partnerships in nanotechnology, will be essential to unlock high-impact breakthroughs in materials for sustainable energy and electrocatalysis.

5.2. Energy Storage and Generation. The rapid global increase in energy consumption demands a shorter timeline between predicting which nanomaterials could be useful for energy production and storage and their successful synthesis, characterization, and device integration. Iterative trial-and-error approaches to discover new materials is too slow to meet current urgent needs, especially related to climate change. Nanoscience has been essential in engineering state-of-the-art PV devices out of multiple materials systems, from interfacial control in

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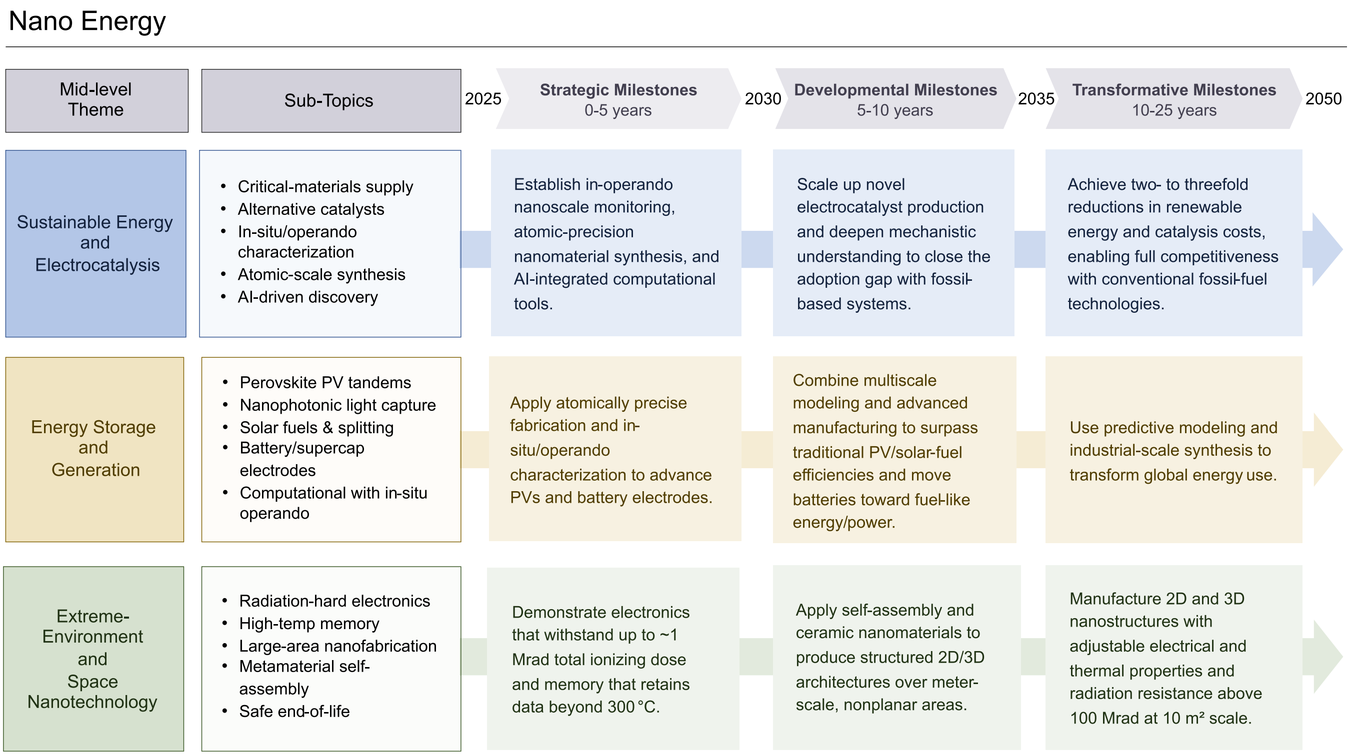
multijunction cells to quantum dot devices to nanophotonics for light guiding and capture. Organic halide perovskites show promise because they combine efficiencies comparable to inorganic PV materials with solution processability and work well when coupled to Si solar cells work well both in single-junction architectures and when coupled with Si solar cellsin tandem geometries. Advances in coatings and nanocomposites to protect against their environmental degradation and improve light management and lifetimes, however, are needed. Nanostructured materials are also key to overcoming the Shockley–Queisser limit on device performance via multiexciton generation and harvesting hot carriers prior to thermalization. Solar fuel production, water splitting, advanced thermoelectrics for waste heat harvesting, photonic engineering for passive radiative heat transfer, luminescent solar concentrators, and new concepts of scintillator devices based on polymer-nanocrystal composites are similarly the domain of nanoscience. In addition, nanomaterials are critical for the design of electrode materials for batteries and supercapacitors, given that their high surface areas and mechanical properties can deviate significantly from bulk.

Breakthroughs in computational methods for guiding exploratory synthesis offer potential to deepen our understanding and accelerate the discovery of next-generation materials like chalcogenide perovskites and chalcohalides. In situ/operando characterization methods of electronic structure and mechanical properties will decrease the timeline between discovery and implementation by orders of magnitude. By 2030, nanoscience advances in atomically precise fabrication and characterization should see gains in both PV technologies and electrode materials for battery applications. Over the next decade, multiscale modeling of materials, as well as energy and charge flow across interfaces, combined with advanced manufacturing methods, will lead to PV and solar fuel production with efficiencies exceeding traditional limits. Likewise, these advanced capabilities will push Li-ion and other battery chemistries toward specific stored energy densities and charge/discharge powers approaching levels of chemical fuels. Predictive modeling and industrial scaling of manufacturing and synthesis of materials for energy applications will have a transformative impact on global energy use by the middle of the century.



5.3. Extreme Environment and Space Nanotechnology. Nanostructured materials for extreme environments—spanning −270 to +1500 °C, 10^{-14} to 10^{9} Pa, and >1 Mrad radiation doses—will be critical in enabling space travel and transportation economies, as well as gigawatt-scale clean energy harvesting projected to be dominant by 2050. Today's best radiation-hard electronics operate reliably up to ∼1 Mrad total ionizing dose (e.g., SiC-based devices) but fail catastrophically beyond 10 Mrad needed for 30-year missions in Jupiter's radiation belts or near nuclear reactors—a 10-times reliability gap. Likewise, nonvolatile memory devices (e.g., flash) cannot sustain information at temperatures exceeding 300 °C. While many nanomaterials have been examined for their robust mechanical and chemical properties, we lack the means to produce nanostructured and metamaterials over large areas and in nonplanar geometries. The ability to create structured functional nanomaterials (photovoltaics, thermoelectrics, radiation hard and mechanically resilient) for energy harvesting in space applications at the >1 m^2 scale, either self-supporting or as coatings, would be game changing.

The fundamental challenge is achieving simultaneous optimization of electronic, thermal, and mechanical properties in nanostructured materials while maintaining atomic-scale precision over meter-scale areas. Current tools like atomic layer deposition are limited to <1 m^2 and planar geometries. We envision that self-assembly techniques to create metamaterial architectures combined with nitride-, carbide-, and oxide-based ceramic nanomaterials could enable 2D and 3D nanostructures

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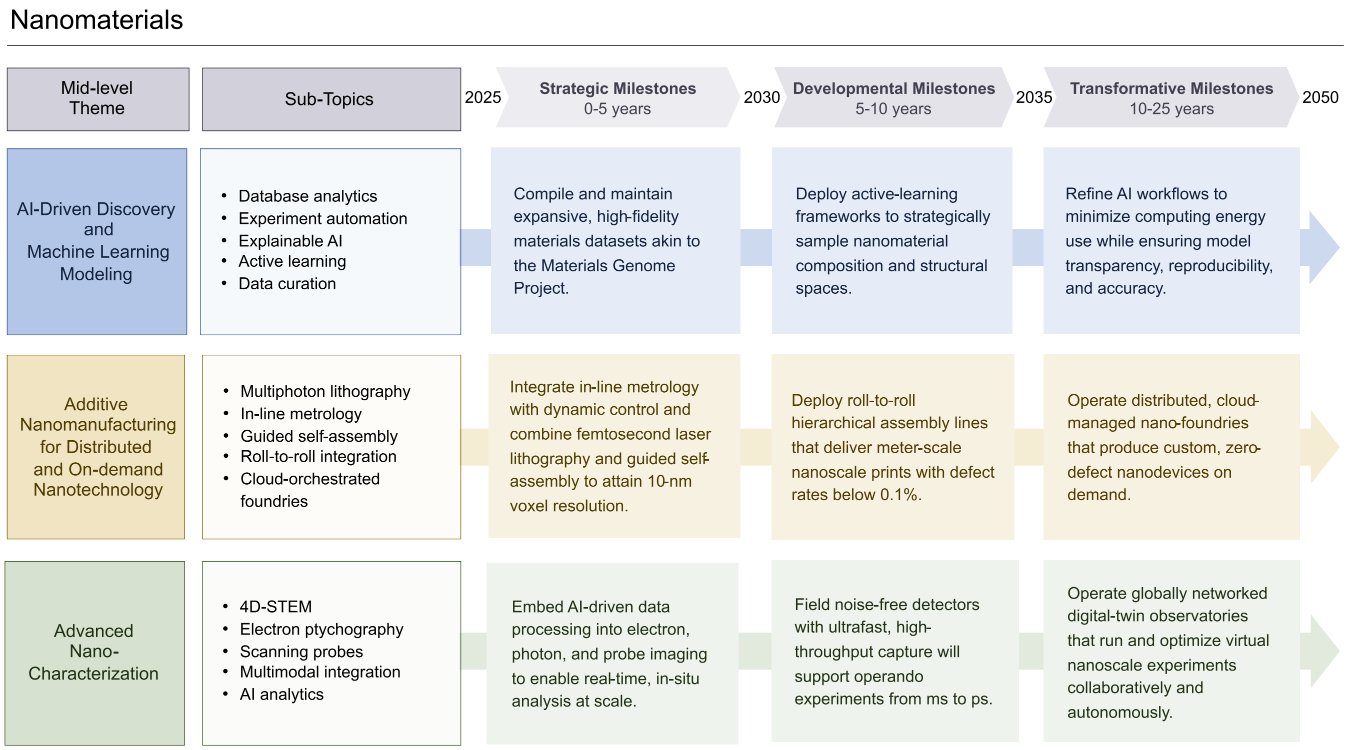
with tunable electrical properties, thermal conductivities, and radiation tolerance exceeding 100 Mrad and at 10-m^2 production capability.

Potential applications abound for solar-powered satellites, space-based solar power stations, and compact nuclear reactors. However, as with other manufactured and nanocomposite materials and protective coatings, care must be taken such that these light, strong, and functional structures only generate safe byproducts, debris, and eventual end-of-life recycling or disposal. Achieving scalable development and deployment of these revolutionary materials will require collaborations among nanofabrication experts, materials scientists, and chemical, industrial, and manufacturing engineers, as well as involvement of space and nuclear power agencies.

6. NANOMATERIALS



6.1. AI-Driven Discovery and Machine Learning Modeling. AI is rapidly transforming the nature and methods of scientific discovery. AI platforms will continue to be trained at scale across all STEM fields and are expected to reach unprecedented levels of accuracy and efficiency while demonstrating an order-of-magnitude expansion each decade. They will build on the success of landmark cases like GNoME (the discovery of 2.2 million stable crystal structures surpassing human chemical intuition) and AlphaFold (a protein-folding prediction system that solved a 50-year-old challenge in biology decades earlier than anticipated). The focus of AI-based discovery will shift to accelerating the search for solid-state battery materials, 2D materials, and neuromorphic nanomaterials, with the goals of enabling long-lived, efficient energy storage and curbing hardware energy consumption. AI-aided breakthroughs are expected to assist in the discovery of novel catalysts for generating biodegradable plastics, developing materials biocompatible with the human immune system, and optimizing quantum materials. This vast and still largely untapped materials space contains an estimated ten trillion possible chemical combinations.

Given the existing successes of AI and machine learning (ML) in nanoscale problems and the enormous power already present in computational chemistry and materials methods across scales (e.g., exact diagonalization, coupled cluster and density functional theory, dynamical mean field theory, molecular dynamics, density matrix renormalization), the stage is set for further breakthroughs in predictive design and synthesis of molecules and materials. On a time scale of 5−10 years, AI-driven research could result in self-driving laboratories that can converge from concept to validated prototype materials in less than 30 days for priority application domains. On a 25-year time scale, we envision creating cloud-based "inverse foundry" services that can deliver manufacturer-ready materials recipes and digital twins on demand, which would compress R&D cycles to days.

Improving the uncertainty, transparency, and reproducibility of complex ML algorithms in predicting nanoscale properties and ensuring data quality remains a major challenge. To solve this problem, we will need to bring more physical insight into ML, with the aim of achieving explainable AI. At the same time, we need to work toward covering the phase space of nanomaterial compositions and structures effectively in our data sets, for example, by developing targeted active-learning strategies. Creation and curation of enormous, reliable data sets are critical. The most transformative applications will require optimizing AI workloads to fully leverage computing infrastructure for scientific discovery, expanding AI use in small-data set research, promoting sustainable algorithms with environmental and energy-consumption monitoring, and upholding performance standards by addressing challenges of reducibility and accuracy. To optimize the benefits of AI in scientific research and ensure its ethical use for the public good, cross-

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sector collaborations between materials scientists and engineers to computer scientists and mathematicians are essential.

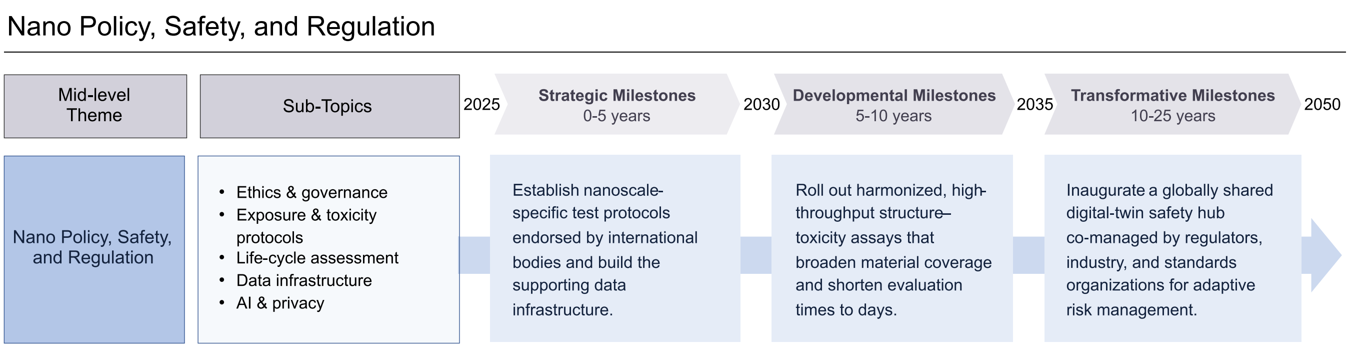
6.2. Additive Nanomanufacturing for Distributed and On-Demand Nanotechnology. Over the next quarter century, we envision that additive manufacturing will achieve nanoscale precision that will revolutionize rapid prototyping of materials and device properties. Much as 3D printing has revolutionized traditional manufacturing, we expect that nanoscale additive manufacturing will reduce the prototyping cycle from months to hours, which will democratize nanotechnology through distributed and custom production and make available capabilities currently limited to the largest semiconductor companies and some small organizations. Current multiphoton lithography systems can achieve 100 nm 3D pixel resolution, pattern many different nanomaterials with different functions, and even incorporate reactive materials to allow for reconfigurable properties, enabling "4D" materials design. Since nanoscale additive manufacturing has much tighter tolerances compared to conventional 3D printing, a core challenge is to integrate 3D multiphoton approaches into roll-to-roll processing with high enough throughput to allow for manufacturing at scale. Although printing single materials under ideal conditions is manageable, simultaneously incorporating multiple materials at different scales requires dynamic feedback to minimize undesirable defects and to stabilize conditions as materials change in response to their ambient environments.

Resolving these challenges will enable 3D and 4D reconfigurable metamaterials and devices to be produced in form factors for wearable electronics, as well as arbitrary surfaces in printed photonics and electronics for a distributed IoT. The increased diversification of nanomaterials in manufacturing and products will pose potential challenges in worker safety, consumer health, and environmental contamination, and so careful consideration of the full lifecycle will be needed to avoid mistakes of previous manufacturing revolutions. We expect that in the next 5 years, systems will incorporate in-line metrology tools and control theory to dynamically tune processing conditions. Bringing together fs-laser lithography and guided self-assembly will achieve 10 nm voxel resolution. In 5−10 years, roll-to-roll hierarchical assembly lines will likely achieve meter-scale throughput with <0.1% defect rates. In the longer term, just as 3D printers and machining tools are readily available in small companies, we anticipate that distributed, cloud-orchestrated nanofoundries can offer on-demand, zero-defect manufacturing of customized devices. Close feedback between the additive manufacturing sectors and semiconductor industries will be needed to bring the disparate tools needed to realize these goals.

6.3. Advanced Nano-Characterization. We expect that nanoscale characterization will accelerate breakthroughs in QIST, computing platforms, energy storage architectures, and bio−nano interfaces by making 3D, subatomic scale resolution in real time and under realistic conditions routine. Today, we are witnessing simultaneous revolutions in microscopy, with new electron, photon, X-ray, and scanning probe imaging modalities. For example, 4D-STEM (scanning transmission electron microscopy) and multislice electron ptychography can resolve atomic positions with sub-Å precision, even providing 3D atomic reconstructions and local electric and magnetic field information. Scanning NV centers, scanning qubit, or tip-enhanced optical spectroscopies can probe single defect states, map quantum transitions, and identify topologically protected states. Automation has allowed imaging of many samples or entire wafers with only minimal human guidance. However, there are two major challenges: (1) the lack of seamless integration across modalities and the inability to perform real-time, in situ and operando analyses at scale for statistically meaningful results and (2) the ability to combine large data sets and multimodal data streams into coherent, interpretable models that can guide autonomous synthesis and decision making.

Imaging modalities will become even more powerful when integrated with AI to accelerate data analysis on massive data sets, increase the autonomy of characterization tools, and streamline the discovery of buried signals or dynamics beyond the reach of today's methods. A breakthrough strategy may involve the development of globally networked "digital twin" observatories, where virtual replicas of nanoscale experiments can be run and optimized collaboratively. This goal requires not only advances in instrumentation, but also robust AI architectures trained on physics-informed models capable of real-time data processing, analysis, and interpretation. By 2035, the development of noise-free electron and photon (X-ray) detectors with high-throughput acquisition capabilities will be essential for real-time monitoring of in situ and operando experiments. These detectors must be capable of capturing phenomena across a broad range of time scales, from chemical reactions occurring on the ms scale to quantum events unfolding within ps. Applications will span from programmable quantum materials to adaptive biomedical implants. However, ethical concerns around data sovereignty and algorithmic bias must be addressed through transparent governance and open-access frameworks. To realize this vision, we must invest in cross-disciplinary consortia connecting AI, microscopy, spectroscopy, and materials science so that a new era of reproducible, scalable, and democratized nanoscience is feasible.

7. NANO POLICY, SAFETY, AND REGULATION



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From the beginning, ethics and safety standards in nanoscience have developed in parallel with scientific and engineering advances because of the promise of nanotechnology for human health and well being, society, and the environment. The nano community aimed to avoid the public backlash that was associated with advances in biotechnology applied to crop growth, protection, and nutrition in the form of genetically modified organisms (GMOs). Hence, groups of economists, ethicists, and researchers worked together to evaluate how best to guide our field for potential impact on society. Still, while scattered frameworks and life-cycle assessments exist, fewer than 20% of commercially used nanomaterials adhere to harmonized International Organization for Standardization (ISO)-aligned exposure and toxicity testing protocols, which leaves a significant gap in our ability to predict and manage material-specific hazard pathways. A major challenge lies in developing integrated, nanoscale-specific test methods endorsed by international standards bodies and then building the data infrastructure needed to support them, since toxicity mechanisms vary dramatically with particle size, shape, and surface chemistry; yet, current regulatory systems remain fragmented and locally tailored. Furthermore, with the burgeoning of AI and massive data sets, there will be increased ethical concerns related to data privacy and human identity, and a proactive approach to safe materials design and a robust regulatory network will be needed.

What was quickly discovered in the research space was that standardization is a major challenge. In a simple but illustrative example—the synthesis of plasmonic nanoparticles—the product is highly dependent on both technical and nontechnical factors, including reagent batch number, reagent purity, calibration of tools used in the synthesis (temperature, agitation), cleanliness of glassware, ambient conditions, and more. Following a published procedure did not necessarily result in the same product. However, more importantly, there was a key, fundamental issue: unlike in chemical synthesis, where a mole of molecules can be synthesized, in nanoparticle synthesis, it is impossible to prepare a mole of nanoparticles. Features such as atomic placement, crystal facets, and stabilizing ligands (to name just a few) cannot be identical for every nanoparticle in the solution. This issue requires the use of statistics to analyze the standardization of nanomaterials and nanodevices, but which has not received enough attention in the literature. The community would greatly benefit from knowing how many devices were tested and how many worked; what the distribution of nanoparticle shapes is in a typical synthesis; and what the tolerance is of composite materials compositions and integrated materials on the performance of batteries, photovoltaic devices, flexible electronics and sensors, and electrocatalysts. Other numerous examples can be included. Establishing ranges of operation based on acceptable nanoscale differences in sample preparation would be enormously beneficial over the next 25 years.

To address these unknowns, by 2035, we need standardized, high-throughput structure−toxicity assays that increase the proportion of tested nanomaterials and reduce test turnaround times from months to days. By 2045, we should scale these capabilities into a full-chain, ISO-aligned life-cycle assessment and safety platform—combining AI-driven predictive models with real-time monitoring via standardized protocols—from lab to field. Finally, by 2050, the goal is to establish a globally shared "digital twin" safety hub co-governed by regulators, industry, and standards organizations, enabling one-stop adaptive risk management and ISO-based certification for all new materials. Achieving this vision will safely enable next-generation drug-delivery vectors, autonomous environmental-remediation swarms, and ultraefficient energy catalysts, while adaptive monitoring and governance protocols will mitigate risks such as bioaccumulation and privacy breaches. Realizing these milestones requires an enduring consortium of academia, industry, regulators, and standards bodies co-building an open nanosafety data hub, unified test-method standards, and a field-validation ecosystem.

In this piece, we have identified key areas where nanofocused research still needs to grow and evolve to approach its potential—for current needs, demands that we can foresee, and future, undefined challenges. Nanoscience insights and tools now touch nearly every technology sector, from the electronics and photonics that we use to process, communicate, and display information; the catalysts that enable enormous diversity of materials and processes; the biomedical advances that monitor and improve our health; and the ways we generate, transport, and store energy. The ubiquity and inherent interdisciplinarity of nanoscience and nanotechnology is its strengths and the root of its foundational importance. Over the next 25 years, massive computational power in the form of AI and ML will enable progress that will likely supersede what has come before. We at *Nano Letters* look forward to continuing to be your home journal for communicating these next great advances and enabling discoveries.

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