

Nanomaterials in Solid-State Physics and Engineering: Synthesis Strategies, Structure-Property Relationships, and Emerging Applications

Nguyễn Lê Văn Thanh¹

¹ Faculty of Applied Sciences, Ho Chi Minh City University of Technology and Engineering (HCM-UTE), 01 Vo Van Ngan Street, Thu Duc Ward, Ho Chi Minh City 700000, Vietnam

ARTICLE INFO	ABSTRACT
Article history: Received: September 12, 2026 Revised: September 18, 2026 Accepted: October 2, 2026 Published: October 20, 2026	Nanomaterials often deliver impressive laboratory metrics, yet translation is weakened when the path from synthesis to operating-state behavior is poorly documented. This review asked whether performance claims could be traced consistently from controllable processing to verified structure, mechanism, function, and a stated translation boundary. Peer-reviewed literature published mainly from 2021 to 31 March 2026 was examined through a narrative review. During major revision, a structured OpenAlex and Crossref audit was added for operando and active-state characterization. The literature showed that size alone rarely determined performance. Surface chemistry, defects, interfaces, and process history often changed the outcome, and in many systems the functional state differed from the pristine or post-mortem structure. Translation problems were most visible when these changes were not connected to realistic measures of loading, yield, stability, or manufacturing compatibility. Stronger studies combined controlled processing with complementary characterization and measurements made under relevant operating conditions. They also made clear where the evidence stopped. Comparison across application areas showed markedly different levels of readiness, from manufacturing-scale evidence in a few device platforms to predominantly laboratory demonstrations in others. On this basis, the review treats the evidence chain as a practical traceability tool rather than a new materials theory and translates it into a domain-adaptable minimum evidence package for engineering claims.
Keywords: nanomaterials; solid-state engineering; structure-property relationships; operando characterization; safe-and-sustainable-by-design	
	<i>This work is licensed under a Creative Commons Attribution-ShareAlike 4.0</i> 
Corresponding Author: Nguyễn Lê Văn Thanh, Faculty of Applied Sciences, Ho Chi Minh City University of Technology and Engineering (HCM-UTE), 01 Vo Van Ngan Street, Thu Duc Ward, Ho Chi Minh City 700000, Vietnam Email: thanhnlv@hcmute.edu.vn	

1. INTRODUCTION

When one or more dimensions enter the nanometer regime, surface energy, defect chemistry, transport, confinement, and interface effects begin to compete on similar length scales. The result is not simply a smaller version of the bulk material. Nanoparticles, nanosheets, nanowires, quantum dots, and nanostructured coatings can show markedly different optical, electrical, magnetic, chemical, or mechanical behavior [1]-[3]. For engineering, however, the useful question is not whether a material is nanoscale. It is whether a controllable process creates a measurable structural state that can explain a reproducible function under relevant operating conditions.

Recent work reflects that shift in emphasis. Studies increasingly focus on synthesis precision and interfacial control [3], lifecycle-aware preparation [16], [17], operando characterization [18], [19], and data-assisted materials discovery [4]-[7]. Application-specific reviews have advanced in parallel, from two-dimensional semiconductors and quantum-dot devices to energy systems, nanomedicine, environmental remediation, and spintronics [13]-[15], [20]-[27]. Together, these literatures show rapid technical progress, but they are often separated by discipline. A synthesis paper may stop at morphology, a device paper at peak performance, and a safety study at exposure. The links among those stages are much less consistently examined.

The gap addressed in this review is therefore one of connection rather than coverage. Existing reviews already describe the major nanomaterial classes and their applications. What is harder to find is a cross-domain account that follows a performance claim back to the evidence that supports it. Was the relevant process

variable actually controlled? Was the proposed structure verified? Was the mechanism observed under conditions close to use? And does the reported metric survive the constraints that appear during translation? These questions matter because a nanoscale advantage is often conditional. More surface can increase reactivity while accelerating parasitic reactions; stronger confinement can sharpen optical control while increasing sensitivity to traps; high capacity at low loading can disappear in a practical electrode. A material-by-material review can easily miss these recurring reversals.

This review is organized around that evidential problem. It follows a recurring path from process control to structural and chemical proof, then to the active-state mechanism, functional validation, and finally the boundary of translation. The framework is not proposed as a new materials theory; it brings together established process-structure-property-performance reasoning, operando analysis, and translation or sustainability constraints. The same lens is then applied across representative mechanisms and application areas to show where the chain is strong, where it is incomplete, and which missing link is most likely to limit engineering use. The review closes by turning this logic into a minimum evidence package whose depth can be adjusted to the application rather than imposed as a universal checklist.

2. METHODS

This manuscript is a narrative review rather than a systematic review or meta-analysis. The literature-coverage window was fixed at 31 March 2026. The original review search used Google Scholar and major publisher/database interfaces, including ScienceDirect, Springer Nature, Royal Society of Chemistry, MDPI, Wiley, and IEEE Xplore where relevant. Search concepts combined 'nanomaterials' with solid-state physics/engineering, synthesis and process control, surface and defect effects, quantum confinement, interfacial transport, operando characterization, AI-guided materials discovery, safe and sustainable by design, and application-specific terms. The review was refined using narrative-review quality principles consistent with SANRA [28]. PRISMA-S informed the reporting of information sources and search concepts, but the manuscript does not claim PRISMA or systematic-review compliance [29].

Peer-reviewed journal articles published mainly between 2021 and March 2026 were prioritized; earlier studies were retained only when needed for conceptual continuity. Source eligibility required a substantive connection to synthesis/process control, characterization, a nanoscale physical mechanism, an engineering application, or translation readiness, together with complete bibliographic information. Retractions, conference/meeting abstracts, editorials used only as commentary, non-peer-reviewed web material, and papers outside the review scope were excluded from the analytical corpus. Screening was conducted as a single-reviewer narrative-review workflow rather than by two independent reviewers. Machine-assisted classification was used only as a prioritization aid during the structured audit described below; it was not treated as an independent reviewer and no final mechanistic claim was accepted solely on an automated label.

Relevance and evidential value were assessed using four dimensions: source eligibility; centrality to the review question; evidence type and strength; and traceability along the evidence chain. Primary experimental studies were prioritized for mechanism and case-study claims, especially when they directly measured active-state behavior, while high-quality reviews were used to establish field-level consensus, boundaries, and translation context. No formal risk-of-bias score was applied because the corpus spans fundamentally different experimental designs and engineering domains. Instead, extracted information was organized by synthesis/process variable, structural or chemical feature, active-state mechanism, functional metric, limitation, reproducibility/scale-up issue, and translation barrier. The thematic subsections of Section 3 therefore constitute the Results and Discussion component of this narrative review rather than conventional experimental results.

Because the original narrative search was not designed as a database census, record-level hit counts for the full review were not preserved and cannot be reconstructed retrospectively without creating false precision. The revised manuscript therefore reports the final analytical corpus (60 unique cited sources after citation deduplication, including the two methodological reporting references) and provides a fully documented structured reproducibility audit for the operando/active-state characterization theme, which is central to the evidence-chain claim. That audit retrieved 600 records from OpenAlex and Crossref, yielded 528 unique records after DOI-based deduplication, and identified 79 objectively source-ineligible records. Of 449 source-eligible records, preliminary triage classified 175 as relevant, 47 as uncertain, and 227 as not central to the theme. The 222 relevant/uncertain candidates were then reviewed against explicit centrality and source criteria; 173 were retained in the thematic evidence pool, and 24 were selected as a compact core-evidence set for critical synthesis. These theme-specific counts are reported as a reproducibility audit, not as a PRISMA flow for the entire narrative review.

Table 1. Search, selection, and evidence-synthesis protocol used in this narrative review.

Protocol summary
Review design / window — Narrative review; 2021 to 31 Mar 2026 prioritized, with earlier sources retained only for essential conceptual continuity.
Sources / search concepts — Original narrative search: Google Scholar and major publisher/database interfaces; concepts included synthesis/process control, characterization, nanoscale mechanisms, applications, AI, operando analysis, and SSbD. Structured operando audit queries: ‘nanomaterials operando characterization’; ‘nanomaterials "in situ" characterization mechanism’; and ‘nanostructures operando spectroscopy microscopy’ in OpenAlex and Crossref.
Eligibility / appraisal — Peer-reviewed, relevant sources with complete bibliographic information; retractions, meeting abstracts, generic web sources, and out-of-scope records excluded. Primary studies prioritized for mechanism; reviews for consensus/context.
Full-review reporting — Original search hit counts were not retained; the revised manuscript contains 60 unique cited sources after DOI/citation deduplication.
Structured operando audit — OpenAlex + Crossref: 600 retrieved -> 528 unique -> 449 source-eligible -> 222 candidates -> 173 retained thematic pool -> 24 core-evidence records. Machine triage served only as a prioritization aid.

For readability, Fig. 1 summarizes the analytic pathway used throughout this review.

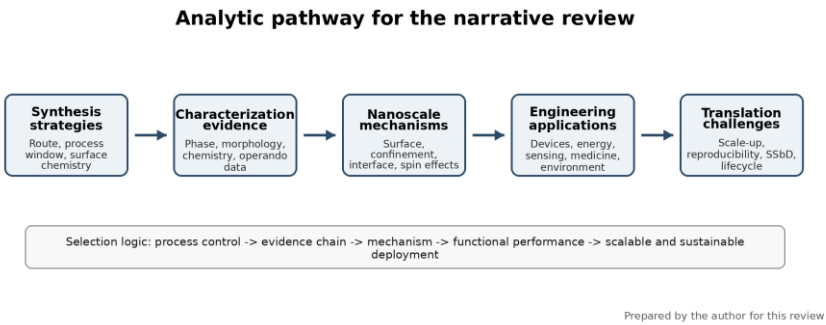


Fig. 1. Review framework connecting synthesis strategies, characterization evidence, nanoscale mechanisms, engineering application domains, and deployment challenges. Source: prepared by the author for this review.

3. RESULTS AND DISCUSSION

3.1. Synthesis Strategies for Nanomaterials

A synthesis label is not, by itself, a sufficient explanation for nanomaterial performance. Two studies can both report a hydrothermal, colloidal, deposition, or milling route yet produce different size distributions, defect densities, interfaces, and surface chemistries because the decisive variables are the process window: precursor activity, supersaturation, temperature history, mixing, residence time, ligand chemistry, substrate condition, atmosphere, and post-treatment. The evidence-chain perspective therefore treats synthesis as a set of controllable process variables that must be linked to the structural feature used to explain function. This distinction becomes more important during scale-up, where heat and mass transfer, mixing efficiency, and residence-time distributions can change even when the nominal recipe is preserved [1], [3], [30].

3.1.1. Top-down routes. Top-down processing is strongest when geometry, registration, and device integration are the dominant requirements. Lithography, etching, focused-ion-beam processing, and related pattern-transfer methods can define channels, contacts, resonators, and arrays with high positional control [3], [20], [31]. The trade-off is that energetic processing can introduce edge disorder, implantation damage, contamination, redeposition, or a broad defect distribution, so the smallest feature is not necessarily the highest-quality functional structure. Mechanical milling illustrates the same principle at larger volume: it is scalable and inexpensive, but particle-size broadening and mechanically generated defects can obscure causal structure-property interpretation. Top-down routes should therefore be evaluated by both dimensional control and process-induced damage, not by feature size alone.

3.1.2. Bottom-up routes. Bottom-up synthesis offers direct control over nucleation, growth, composition, doping, shell formation, and surface termination, which is why it dominates many quantum-dot, oxide, nanowire, heterostructure, and colloidal systems [1], [3]. Its apparent precision, however, is highly conditional. Small shifts in supersaturation, precursor conversion, ligand binding, pH, mixing, or heating rate can change

nucleation density and subsequent growth, while purification and ligand exchange can alter the same surfaces that govern optical, catalytic, or electrochemical behavior. A credible bottom-up claim therefore requires reporting the variables that define the nucleation-growth trajectory rather than presenting temperature and reaction time as a complete recipe.

Hydrothermal and solvothermal routes remain attractive for phase-selective growth under accessible conditions, whereas thermal decomposition and colloidal methods can provide narrower nanocrystal distributions and stronger surface-passivation control. Vapor-phase growth is preferable when lateral continuity, epitaxy, or heterointerface quality is central to device performance [20], [13], [14]. These advantages do not transfer automatically to larger reactors or larger substrates. Increasing batch size changes mixing time, thermal gradients, precursor transport, and local supersaturation; increasing wafer area introduces additional non-uniformity in flux, temperature, and surface condition. Recent manufacturing analyses therefore emphasize continuous or semi-continuous processing, real-time process analytical technology, and explicit critical-process-parameter/critical-quality-attribute relationships as strategies for improving reproducibility rather than assuming geometric scale-up is neutral [30].

3.1.3. Green and sustainable synthesis. Lower-toxicity solvents, biological reducing agents, aqueous processing, and lower-temperature routes can reduce selected environmental or occupational burdens [16], [17], [22], [25], [26]. However, the term 'green synthesis' should not be treated as evidence of overall sustainability. Biogenic extracts can contain poorly defined reducing and capping species, causing batch-to-batch variation in particle size, composition, and surface chemistry, while a lower-hazard solvent can be offset by poor yield, difficult purification, high energy use, or problematic end-of-life release. Safe-and-sustainable-by-design approaches therefore require life-cycle and risk questions to be considered alongside nanoscale control rather than after performance optimization [32]. Early-stage SSbD case studies also show that practical application remains data-intensive and sensitive to the choice of functional unit and nano-specific descriptors. Thus, the relevant comparison is not conventional versus 'green' as labels, but functional equivalence, reproducibility, hazard, resource intensity, and lifecycle consequence.

3.1.4. Precision coatings and conformal growth. For integrated nanomaterials, coating quality is often more important than nominal coating composition. Atomic layer deposition and related conformal-growth methods can passivate defects, regulate charge transfer, suppress parasitic reactions, and stabilize buried interfaces [31]. Yet a coating described only by average thickness can conceal incomplete coverage, pinholes, islands, or pore blockage. A 2024 lithium-ion cathode study is illustrative: with the coating concentration held constant, changing deposition conditions altered coating homogeneity, and more homogeneous coverage reduced charge-transfer resistance and improved high-voltage cycling stability [33]. The engineering variable was therefore not simply 'coated versus uncoated' but spatial coverage and interfacial continuity. This example supports a broader requirement that coating studies verify morphology and chemistry with complementary depth and area sensitivities rather than infer protection from precursor amount alone.

3.1.5. Artificial-intelligence-guided synthesis and autonomous laboratories. Data-driven planning and closed-loop experimentation can explore high-dimensional process spaces more efficiently than sequential one-factor-at-a-time optimization [4]-[7], [34]. Their main value is experimental prioritization: algorithms can suggest the next composition or process condition, while robotics and automated characterization shorten the feedback cycle. The limitation is epistemic as well as technical. Models trained on incomplete synthesis metadata, successful experiments only, or a narrow laboratory platform can optimize correlations that do not transfer to another reactor, substrate, or measurement protocol. For nanomaterials, AI-guided synthesis is therefore best treated as a search and control layer whose recommendations still require mechanistic validation, uncertainty reporting, and explicit out-of-domain testing. Autonomous discovery does not remove the need to identify which process variable actually created the functional structure.

3.1.6. Scale-up and reproducibility as synthesis variables. Scale-up should be considered part of synthesis science rather than a downstream manufacturing problem. Increasing throughput can change mixing, shear, heat removal, residence time, solvent removal, and interfacial stress, thereby shifting the very particle size, morphology, or defect population that generated the laboratory result. Continuous-manufacturing analyses of nanomaterial products emphasize tighter control of critical process parameters and in-line or on-line measurement as ways to reduce batch variability [30]. Application-level examples show why this matters: high-area-loading silicon nanoparticle anodes require mechanical stabilization at the current-collector interface, and a design that performs at low loading cannot be assumed to retain its behavior after electrode thickness and stress increase [35]. Accordingly, the most informative scale-up evidence reports not only a larger batch or device, but whether the relevant structural descriptors and performance distributions remain within a defined window.

No synthesis family is intrinsically superior. The useful choice depends on the variable that must be controlled. Top-down methods are strongest for registration and integration; bottom-up methods for composition and interfaces; conformal growth for buried surfaces; and continuous or autonomous workflows for tighter process exploration and reproducibility. Sustainable routes add a different constraint by forcing hazard and lifecycle questions into the design stage. Across these approaches, the same test remains useful: the process variable should produce a measured structural consequence, that consequence should account for function, and the relationship should survive the changes in throughput, substrate, or batch that accompany translation.

Because review articles benefit from compact comparative views, Table 2 condenses the principal synthesis families discussed in Section 3.1 and clarifies where each route is most useful.

Table 2. Analytical comparison of major nanomaterial synthesis routes, emphasizing process variables, structural consequences, trade-offs, and scale-up risks.

Route family	Critical process variable	Structural consequence	Engineering benefit	Trade-off / scale-up risk	Refs.
Top-down	Dose/energy, milling intensity, feature geometry	Pattern dimensions, edge/defect density, contamination	Registration, patterning, direct device integration	Damage and defect generation can rise as feature size falls; tool transfer may alter damage profile	[1], [3]
Wet-chemical bottom-up	Supersaturation, pH, ligand chemistry, mixing, temperature history	Size/shape distribution, phase, surface termination, shell quality	Fine composition and surface control	Highly sensitive to mixing and nucleation history; purification and ligand residues affect function	[1], [17], [3]
Vapor / conformal deposition	Flux, surface reaction, substrate temperature, cycle chemistry	Film continuity, interface abruptness, conformality, defect density	High-quality films and buried-interface control	Area scale-up creates flux/temperature non-uniformity; equipment and substrate-window limits	[20], [31]
Green / bio-assisted	Reducing/capping chemistry, extract composition, solvent, energy input	Surface chemistry and particle distribution	Potentially lower solvent/precursor hazard	Biological feedstocks can reduce reproducibility; sustainability depends on yield, purification and lifecycle	[16], [17], [32]
AI-guided / autonomous	Search policy, descriptor quality, feedback measurements	Optimized process window rather than one fixed structure	Faster exploration of multidimensional spaces	Domain shift, sparse negative data, metadata quality and platform dependence	[4]-[7], [34]
Continuous / scale-up-oriented	Flow, residence time, mixing, heat transfer, in-line control	Tighter distribution of critical quality attributes	Throughput with real-time process control	Requires validated CPP-CQA relations and instrumentation; scaling remains material-specific	[30], [35]

3.2. Characterization Across Length and Time Scales

Characterization is the point at which a synthesis claim becomes a mechanistic claim. For nanomaterials, nominal composition is rarely sufficient because size distribution, phase, defect density, local oxidation state, surface termination, ligand environment, aggregation, and interface quality can all alter function. Electron microscopy, diffraction, vibrational spectroscopy, and surface-sensitive spectroscopy therefore provide complementary rather than interchangeable evidence. Microscopy resolves morphology and local structure; diffraction establishes average phase and crystallinity; Raman, infrared, and X-ray photoelectron spectroscopy probe bonding, disorder, and surface chemistry; and application-relevant electrical, optical, electrochemical, or mechanical measurements establish whether those structural states actually matter to function. The critical point is evidential convergence: a persuasive structure-property claim should not rest on a single micrograph or spectrum when several distinct structural explanations remain plausible [3], [18], [19].

3.2.1. From pristine structure to the active state. The major methodological shift in recent nanomaterials research is from static post-mortem characterization toward time-resolved, in situ, and operando measurements. This shift is not merely an instrumentation upgrade. Many functional nanomaterials reconstruct

under bias, illumination, electrochemical cycling, gas exposure, thermal loading, or mechanical stress, so the state that determines performance may differ substantially from the state measured before operation. Cross-platform operando studies emphasize that early and transient transformations can control later behavior and may be missed when only initial and final states are compared [18]. In situ and operando electron microscopy likewise show that phase transformations, interface motion, defect evolution, and morphology changes can be stimulus dependent at the nano- and atomic scales [36], [37]. Consequently, the evidential question is no longer only “what structure was synthesized?” but “what structure and chemistry exist while the material is performing its intended function?”

3.2.2. Complementarity is essential for mechanism assignment. No single technique simultaneously resolves morphology, phase, oxidation state, buried-interface chemistry, electronic structure, and functional response at the same spatial and temporal resolution. Strong mechanism claims therefore arise from correlated measurements in which each method closes a different evidential gap. A representative example is oxygen-evolution electrocatalysis, where correlative operando microscopy showed voltage-driven transformation of cobalt hydroxide into more oxidized active states and linked local Co^{3+} enrichment at reactive edge sites to catalytic current [38]. A second example is CO_2 electroreduction, where operando electrochemical 4D-STEM combined with X-ray spectroscopy captured reduction, disordering, migration, and restructuring of copper nanowires during operation [39]. These studies illustrate why a pristine-state TEM image or ex-situ oxidation-state assignment can be insufficient: the relevant mechanism emerges only when spatial, chemical, temporal, and functional evidence are aligned.

3.2.3. Dynamic and interfacial degradation in battery materials. Operando mapping of metal dissolution and redeposition near battery-electrode surfaces has shown that reconstruction and dissolution pathways vary with state of charge and that local chemical trapping can shift the dissolution-redeposition equilibrium [40]. In lithium-sulfur systems, operando confocal Raman microscopy resolves the generation, transport, and consumption of polysulfide intermediates during cycling, linking reaction pathways to electrode conductivity and cell performance [41]. Surface-sensitive operando XPS further demonstrates that the solid-electrolyte interphase develops chemically during operation rather than existing as a fixed post-mortem layer [42]. Together, these cases show that translation-relevant failure mechanisms often reside at dynamic interfaces; bulk-averaged or post-mortem measurements can identify degradation products without establishing when, where, or why the degradation pathway emerged.

3.2.4. Device-level active-state evidence beyond electrochemistry. In two-dimensional WS_2 gas sensors, simultaneous ambient-pressure XPS and electrical measurements directly connect adsorption-induced surface chemistry with changes in resistivity under realistic gas exposure [43]. In quantum-dot light-emitting diodes, operando observation of ZnO transport-layer recrystallization links ion-driven structural evolution and defect passivation with improved carrier transport and external quantum efficiency [44]. These examples are important because they move characterization from material description to engineering diagnosis: the measurement identifies a controllable structural or interfacial variable that explains a device metric. Such evidence is stronger than reporting high performance alone because it makes the causal chain from active-state structure to function explicit.

Operando evidence also requires interpretive caution. Specialized cells can impose non-standard geometries, pressure, electrolyte volume, optical access, or current distribution; electron and X-ray beams may perturb sensitive materials; and a highly localized probe may not represent a heterogeneous device. The appropriate response is not to reject operando methods but to report their boundary conditions and to cross-check them with complementary probes, replicate measurements, and realistic performance tests [36], [37]. The strongest studies distinguish direct observation from inference and identify which parts of the mechanism remain unresolved. This distinction is particularly important when a proposed active state is short-lived, spatially localized, or accessible only under a modified measurement environment.

Automated analysis is also changing how large characterization datasets are handled, particularly in microscopy, spectral deconvolution, anomaly detection, and multimodal data fusion [6], [7], [19]. Its most convincing role is to extend causal analysis, not to substitute for it. A model can expose weak patterns across images or spectra, but those patterns remain only as reliable as the calibration, metadata, preprocessing, and physical validation behind them. For that reason, data-driven characterization is treated here as part of the evidence chain rather than as an independent source of mechanistic truth.

3.3. Structure-Property Relationships in Nanomaterials

Nanomaterials are scientifically interesting because several characteristic lengths can become comparable at once. Particle dimensions may approach an exciton radius, a depletion width, a diffusion length, a phonon mean free path, or the thickness of an interface. Under those conditions, surfaces, defects, confinement,

transport, and interfaces do not act independently. Improving one feature can disturb another. The discussion that follows therefore focuses on trade-offs rather than on isolated nanoscale advantages, and asks which structural variable actually controls the measured response.

3.3.1. Surface-dominated behavior and defect trade-offs. Increasing surface-to-volume ratio is a well-established nanoscale effect, but its engineering consequence is bidirectional. More exposed surface can increase adsorption, catalytic turnover, electrochemical accessibility, and sensor response; the same increase can also amplify oxidation, ligand loss, dissolution, trap-assisted recombination, and batch-to-batch variability. Defect engineering illustrates this tension clearly. Vacancies, heteroatom defects, strained coordination environments, and under-coordinated surface atoms can create catalytically active electronic states, yet excessive or poorly controlled defect densities can lower structural stability, broaden energetic disorder, or accelerate parasitic reactions [46]. The key design variable is therefore not simply 'more surface' or 'more defects', but a reproducible defect population embedded in a chemically stable surface environment. For colloidal and solution-processed nanomaterials, ligand identity, ligand density, solvent history, and post-synthetic exchange can be as important as core composition because they control both passivation and interparticle transport. Mechanistic claims are strongest when activity gains are accompanied by evidence that distinguishes active defects from degradation-induced defects and when stability is measured under the same conditions used to claim improved performance.

3.3.2. Quantum confinement and conditional device benefit. The size-dependent shift of electronic states when semiconductor dimensions approach the excitonic confinement regime is a mature physical mechanism, and it underpins the tunable absorption and emission of quantum dots and thickness-dependent electronic structure in low-dimensional semiconductors [20], [13]-[15]. What is less universal is the assumption that stronger confinement automatically improves a device. As size decreases, the fraction of atoms at or near the surface increases, making trap density, ligand binding, shell quality, Auger processes, and dielectric environment increasingly important. Recent QD-LED reviews identify efficiency, operational stability, and short blue-emitter lifetime as persistent commercialization constraints even after substantial gains in internal efficiency [47]. Perovskite-QD literature similarly shows that surface vacancy defects and ligand chemistry directly influence charge transport and non-radiative recombination, so passivation must be co-optimized with confinement rather than treated as a secondary correction [48]. Operando work on ZnO-based QLEDs provides a concrete example: defect-passivating recrystallization of the electron-transport layer simultaneously reduced carrier density and increased mobility, raising external quantum efficiency from 17.2% to 33.7% [44]. The broader lesson is that the size-band-gap relationship is established physics, whereas the translation from confinement to superior device performance remains interface- and architecture-dependent.

3.3.3. Interfacial transport and heterostructure effects. At nanoscale dimensions, interfaces can dominate electrical behavior even when the constituent materials have attractive intrinsic properties. This is especially clear in two-dimensional transition-metal dichalcogenide transistors, where atomically thin channels suppress some short-channel effects but metal/semiconductor contacts introduce Fermi-level pinning, Schottky barriers, process-induced defects, and contact resistance that can overwhelm channel mobility [49], [50]. Strategies such as transferred metals, van der Waals contacts, interface decoupling, and charge-transfer doping can reduce contact damage or improve carrier injection, but they introduce their own constraints in process temperature, reproducibility, p-type operation, dielectric integration, and wafer-scale manufacturing. Thus, a high intrinsic mobility value is not sufficient evidence of device readiness. The relevant evidence chain is contact formation process $\rightarrow$ interfacial disorder and band alignment $\rightarrow$ injection barrier/contact resistance $\rightarrow$ transistor current and switching metrics $\rightarrow$ process compatibility and yield. This distinction also clarifies why interface-sensitive characterization is complementary to bulk transport measurements: electrical data can demonstrate a resistance penalty, but spectroscopic and structural evidence is needed to assign whether the cause is chemical disorder, defect-induced gap states, barrier formation, or another interfacial mechanism.

3.3.4. Magnetic and spin-dependent behavior. Size-dependent magnetic anisotropy, domain structure, and superparamagnetic transitions are established features of magnetic nanostructures, whereas several device concepts based on emergent magnetic textures remain at a less mature stage. In magnetic tunnel junctions and spin-orbit-torque devices, interface roughness, oxidation, crystallographic texture, magnetic dead layers, and spin-transparency losses can be as important as the nominal magnetic material itself. Recent spintronics reviews describe continuing gains in magnetic-tunnel-junction performance, spin-charge conversion, and skyrmion control, but they also emphasize thermal stability, defect tolerance, fabrication complexity, and integration with semiconductor processing as major barriers to large-scale deployment [27], [27]. The evidence should therefore be graded by maturity. Tunnel magnetoresistance and interface-controlled anisotropy are supported by extensive experimental literature; room-temperature skyrmion devices, two-dimensional magnets, and some neuromorphic spintronic architectures are promising but remain more dependent on specific

material stacks, device geometries, and fabrication conditions. Presenting these categories separately avoids turning rapidly evolving demonstrations into universal design rules.

3.3.5. Mechanical, thermal, and multifunctional coupling. Nanostructuring changes load transfer and heat flow because interfaces interrupt continuum behavior. In polymer nanocomposites reinforced by two-dimensional fillers, mechanical gain depends not only on filler stiffness but also on aspect ratio, orientation, interfacial adhesion, defect density, dispersion, agglomeration, and volume fraction [51]. Increasing filler loading can improve network formation and stress transfer up to a point, but agglomeration can introduce voids and stress concentrators while simultaneously degrading processability. Thermal transport exhibits an analogous trade-off. High-conductivity nanosheets or nanofillers can create efficient heat-spreading pathways, yet interfacial thermal resistance and phonon scattering can dominate if interfaces are weakly coupled or geometrically mismatched [52], [53]. Consequently, 'lower thermal conductivity through boundary scattering' and 'higher thermal conductivity through percolating fillers' are not contradictory claims; they correspond to different architectures and transport objectives. The relevant parameters are interface density, phonon-spectrum mismatch, bonding, orientation, percolation, and characteristic feature size. These dependencies are well established qualitatively, but quantitative optimization remains strongly system specific and should be reported with processing history, filler dispersion, interface chemistry, and uncertainty rather than as a material-intrinsic constant.

3.3.6. Cross-domain evidence-chain comparisons. The evidence chain becomes clearest when the full sequence is visible in a specific system. In QLEDs, transport-layer chemistry and ion-assisted processing can promote ZnO nanoparticle coalescence and defect passivation. Lower carrier density and higher mobility then reduce non-radiative loss and improve electron injection; one operando study reported an increase in external quantum efficiency from 17.2% to 33.7% [44]. The open questions are no longer about the existence of the effect, but about its reproducibility, long-term stability, pixel-scale uniformity, and compatibility with manufacturing. A different chain appears in Mn-containing battery cathodes. Electrode and interface formulation alter dissolution-redeposition dynamics, while operando measurements link state-of-charge-dependent reconstruction and Jahn-Teller distortion to Mn loss. Local trapping of dissolved Mn by a sulfonated polymer shifted that equilibrium and improved performance [40], although the strategy still needs validation at high loading and long cycle life. In two-dimensional transistors, the limiting link is often the contact rather than the channel: fabrication history affects interface disorder and Fermi-level pinning, which set the Schottky barrier and contact resistance even when the channel mobility is high [49], [50]. These examples reach the same conclusion by different routes. A high property value becomes engineering evidence only when the processing variable, structural state, operative mechanism, functional metric, and deployment constraint can be followed in sequence. Fig. 2 summarizes these coupled relationships.

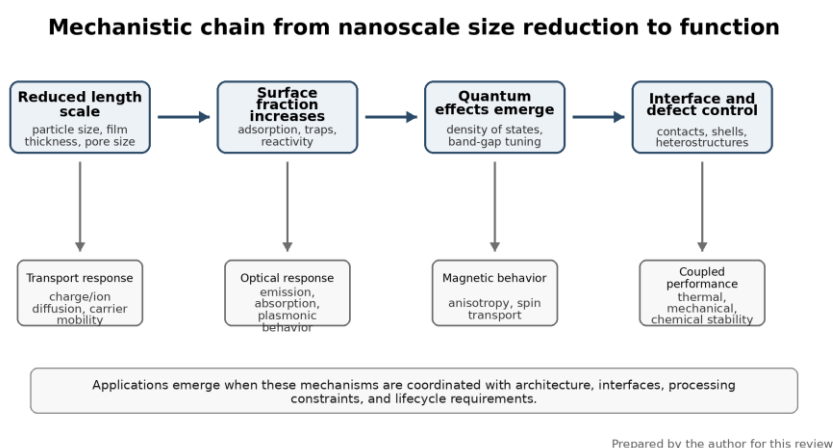


Fig. 2. Mechanistic chain linking nanoscale size reduction to surface, quantum, interfacial, transport, optical, magnetic, and multifunctional behavior. Source: prepared by the author for this review.

3.4. Application Domains

3.4.1. Nanoelectronics and optoelectronics. Translation maturity differs sharply within this domain. Two-dimensional transition-metal dichalcogenide electronics have progressed from isolated proof-of-concept devices toward more reproducible integration, but current reviews identify material defects, contact

engineering, doping, and industry-compatible dielectrics as immediate barriers rather than intrinsic channel mobility alone [49]. This distinction matters because a high-mobility flake is not equivalent to a manufacturable transistor technology; contact resistance, device-to-device variation, wafer-scale uniformity, thermal budget, and yield become the more relevant engineering metrics. The nanoscale opportunity is therefore inseparable from interface control and process compatibility.

Quantum dots represent a more mature but still conditional optoelectronic case. Size-controlled emission, core-shell engineering, and solution processing have enabled impressive QD-LED efficiencies and have already supported commercial quantum-dot display architectures. For electroluminescent QD-LEDs specifically, however, commercialization is still constrained by operational stability, the short lifetime of blue devices, cadmium-free performance, ZnO-related consistency, and patterning for high-resolution displays [47]. Operando evidence that ZnO transport layers can recrystallize during device operation further shows why as-fabricated structure is not always the relevant device state [44]. The translation criterion is therefore not peak external quantum efficiency alone, but efficiency-lifetime-yield consistency within a scalable patterning and encapsulation process.

3.4.2. Energy storage and conversion. Nanostructuring can shorten diffusion lengths, increase electrochemically active area, and enable strain accommodation, but the same features can increase parasitic interfacial reactions, electrolyte consumption, surface-film growth, and mechanical instability [21], [22]. Translation therefore changes the metric set. Gravimetric capacity measured in a lightly loaded half-cell is insufficient when commercial relevance depends on areal loading, electrode density, electrolyte quantity, full-cell balance, Coulombic efficiency, cycle retention, and manufacturability. A recent high-areal-loading silicon nanoparticle study achieved a 6.13 mg cm^{-2} anode using an elastic CNT buffer to manage interfacial stress, but the full cell still showed substantial capacity fade by 100 cycles [35]. Likewise, cathode-coating work shows that identical coating concentration can produce different high-voltage stability when coverage homogeneity changes [33]. These examples illustrate why energy nanomaterials should be benchmarked under loading, geometry, and cycling conditions that preserve the proposed mechanism while approaching practical constraints.

3.4.3. Biosensing and nanomedicine. Nanoscale optical, electrochemical, and magnetic transduction can amplify weak biochemical interactions, while nanocarriers can alter solubility, exposure, and tissue distribution [23], [24], [54]. Yet analytical or preclinical performance often degrades when a controlled buffer or animal model is replaced by heterogeneous biological matrices and clinically relevant manufacturing. For biosensors, limits of detection should therefore be accompanied by selectivity, matrix interference, calibration stability, lot-to-lot variation, and sample-preparation burden. For nanomedicine, the DELIVER framework identifies poor physicochemical understanding, inadequate exposure at the target tissue, limited reproducibility from preclinical to clinical settings, biocompatibility, industrial scale-up, GMP, and regulatory navigation as distinct translation barriers [55]. This domain provides a strong warning against treating nanoscale functionality as sufficient evidence of deployment readiness: surface chemistry, protein corona, storage stability, dose reproducibility, and manufacturing controls can dominate the path from laboratory efficacy to clinical use.

3.4.4. Environmental remediation. High surface area, adsorption sites, photocatalysis, and redox activity can produce high contaminant-removal efficiencies in controlled batch tests [25], [26], [56], but translation requires testing in realistic matrices and tracking the nanomaterial as well as the pollutant. Transformation, aggregation, fouling, dissolution, and recovery can alter both performance and exposure. A 2024 pilot wastewater-treatment study using isotopically enriched silver nanoparticles and gold nanoparticles showed that transformations through the treatment process reduced nanoparticle uptake under environmentally relevant exposure scenarios [57]. The result is important methodologically: behavior inferred from pristine nanoparticles at artificially high concentration may not represent the transformed material encountered in the environment. Environmental claims are therefore stronger when removal or catalytic performance is paired with recovery, leaching, transformation, reuse, realistic concentration, and lifecycle exposure data.

3.4.5. Spintronics and magnetic systems. This domain demonstrates why evidence maturity should be assigned to a specific device class rather than to 'spintronics' as a whole. Spin-transfer-torque MRAM (STT-MRAM) has reached commercial manufacturing and is being positioned as embedded non-volatile memory for advanced nodes, providing unusually strong translation evidence for a nanoscale spin-dependent technology [58]. By contrast, spin-orbit-torque MRAM, voltage-controlled magnetic anisotropy concepts, antiferromagnetic tunnel junctions, and several spin-logic architectures remain at earlier stages where switching current, field-free operation, endurance, integration, and back-end-of-line compatibility are still active research problems [27]. The relevant nanoscale variables—magnetic anisotropy, tunnel-barrier quality, spin-charge conversion, interface roughness, and thermal stability—must therefore be interpreted together with array-level error rates, write energy, endurance, and fabrication yield.

3.4.6. Comparative translation maturity. The reviewed domains do not support a single claim that nanomaterials are uniformly 'close to application.' Translation is strongest where the field reports manufacturing-compatible metrics and system-level reliability rather than only material-level performance. Among the examples considered here, STT-MRAM provides the clearest case of commercial-scale deployment [58]. QD optoelectronics are technologically advanced, although electroluminescent QD-LEDs retain stability and patterning barriers [47]. Two-dimensional semiconductor electronics and nanostructured energy electrodes have strong device-level demonstrations but still face yield, contact/interface, loading, full-cell, and process-control gaps [49], [35]. Nanomedicine has approved nanotechnology products yet remains highly sensitive to biological exposure, reproducibility, GMP, and regulatory constraints [55], while environmental applications require realistic transformation and lifecycle evidence before laboratory removal efficiency can be interpreted as safe deployment [57]. This ranking is therefore evidence-based and domain-specific rather than a universal technology-readiness scale.

Across these applications, the limiting question is rarely whether a nanomaterial can produce a high intrinsic performance value. The harder test is whether the structural feature responsible for that value survives realistic loading, area, concentration, dose, temperature, cycle number, or throughput. Translation metrics therefore have to match the domain: yield and contact resistance in electronics, loading and full-cell balance in batteries, selectivity and matrix effects in sensing, exposure and manufacturability in nanomedicine, or recovery and leaching in environmental use. This is why a single generic notion of 'technology readiness' is less informative than an explicit account of the constraint that has actually been tested.

Table 3. Cross-domain comparison of nanoscale mechanism, translation-relevant metrics, bottlenecks, and evidence maturity.

Application domain	Critical nano-feature / mechanism	Translation-relevant metric	Principal bottleneck	Evidence maturity	Refs.
Nanoelectronics / optoelectronics	2D interfaces and contacts; QD confinement, shell/passivation and charge balance	Contact resistance, device yield/uniformity; EQE plus lifetime and patterning yield	Defects, contacts/dielectrics, ambient stability; blue-QD lifetime and scalable patterning	Mixed: QD optoelectronics advanced; 2D electronics pre-industrial	[47], [49], [44]
Energy storage / conversion	Short transport paths, interfacial kinetics, strain accommodation and protective coatings	Areal loading/capacity, full-cell balance, Coulombic efficiency, cycle retention	Side reactions, interfacial stress, electrolyte demand, coating/process reproducibility	Advanced laboratory evidence; manufacturing and durability gap remains	[21], [33], [35]
Biosensing / nanomedicine	Surface-mediated recognition, signal amplification, controlled transport and biodistribution	Selectivity in real matrices; exposure, dose reproducibility, stability, GMP readiness	Protein corona, biological variability, scale-up, biocompatibility and regulation	Application-dependent; clinical translation requires substantially more than nanoscale efficacy	[23], [24], [55]
Environmental remediation	Adsorption/redox-active surfaces and photocatalysis coupled to transformation in real matrices	Removal under realistic matrices, reuse/recovery, leaching, transformed-particle exposure	Fouling, transformation, recovery, release and lifecycle uncertainty	Mostly pilot/lab-to-field transition; realistic exposure evidence still limited	[25], [56], [57]
Spintronics / magnetic memory	Magnetic anisotropy, tunnel magnetoresistance, spin torque and interface quality	Write energy/current, endurance, retention, error rate and fabrication yield	Thermal stability, switching efficiency and integration compatibility	Heterogeneous: STT-MRAM commercial; SOT/AFM and spin logic emerging	[58], [27]

3.5. Emerging Directions, Evidence Maturity, and Translation

One fast-moving area is AI-enabled experimentation. Machine-learning workflows and self-driving laboratories now support candidate screening, synthesis planning, experiment selection, and data interpretation at a scale that is difficult to achieve manually [4]-[7], [34]. The benefit is clear when the process space is high-dimensional. The weakness is equally clear: performance depends on metadata quality, transferability, reliable automation, and human oversight. Autonomous experimentation is therefore treated here as emerging research infrastructure, not as a reason to relax mechanistic validation.

A more experimentally mature change is occurring in characterization. Time-resolved and environment-aware methods are moving mechanism assignment away from pristine-state snapshots and toward the state that actually exists during operation. The studies discussed in Section 3.2 show surfaces and interfaces that reconstruct, dissolve, recrystallize, or change oxidation state under load [38], [40], [44]. That evidence is persuasive, but it is not automatically representative: realistic cells, sampling volumes, and complementary probes remain uneven across the literature. Operando measurements are strongest when the temporal and environmental limits of the observation are made explicit [18].

Sustainability is changing the design question as well. Safe-and-sustainable-by-design (SSbD) approaches move hazard, exposure, resource use, recyclability, and lifecycle effects upstream, before a material is optimized around performance alone. Applying the European SSbD framework to graphene-based materials shows both the value of this approach and its current data burden [32]. Nanomedicine offers a parallel lesson: translational frameworks treat reproducibility, manufacturability, regulation, and scale-up as design variables rather than late-stage checks [55]. The endpoints differ by domain, but the underlying message is the same: a peak laboratory metric is not a complete measure of a material's engineering value.

These developments converge on a practical problem of traceability. A performance gain is much easier to trust when it can be followed back to a controlled process variable and a verified structural state, then forward to a mechanism measured under relevant conditions. Scale-up exposes the weakness of that chain because mixing, heat transfer, loading, interface chemistry, and manufacturing sequence all change at once. The purpose of the framework used here is to make those breaks visible rather than to imply that every study must already solve them.

3.5.1. Positioning of the evidence-chain framework. The framework used here is not intended as a new theory of materials design. Its purpose is more practical: to place several established ways of reasoning in the same line of sight. Systems materials design and ICME/PSPP already connect processing, structure, properties, and performance while accounting for uncertainty [59], [60]. Data-driven studies add multivariable relationships and faster search of process space [45], [34]. Operando methods add a different demand: when a material changes during use, the structure used to explain function should be the active one rather than only the as-synthesized state [18], [38]. DELIVER and SSbD then extend the discussion toward manufacturing, regulation, safety, and lifecycle constraints [55], [32]. The evidence chain does not replace these approaches. It uses them to ask, in one sequence, whether a claim remains traceable from processing to the point where translation becomes uncertain.

Table 4. Relationship between established materials-development approaches and the evidence-chain framework used in this review.

Approach	Core emphasis	What it captures well	Gap for a cross-domain nanomaterials review	Role in this review
Systems materials design / Materials by Design [59]	Goal-oriented linkage of process path, structure and properties with uncertainty	Design logic across interacting subsystems and scales	Does not by itself require active-state validation or domain-specific translation endpoints	Provides the systems-design foundation
ICME / PSPP linkage [60]	Process -> structure -> property -> performance	Causal linkage and multiscale computational integration	Often optimized for a defined materials/process class rather than heterogeneous nano-applications	Provides the backbone of the evidence chain
Data-driven nanomaterial design [45]	Multivariate synthesis-structure-property learning	High-dimensional descriptors, prediction and inverse design	Correlations remain vulnerable to metadata quality, domain shift and hidden confounding	Supports discovery but does not replace physical validation

Approach	Core emphasis	What it captures well	Gap for a cross-domain nanomaterials review	Role in this review
Operando / active-state characterization [18], [38]	Structure and chemistry under working conditions	Reconstruction, transient states, interfacial and temporal mechanisms	Expensive, probe-limited and not always representative of full-scale operation	Adds the active-state mechanism requirement
Self-driving laboratories [34]	Automated closed-loop experiment selection and optimization	Rapid search of process/composition spaces and reproducible workflow execution	Autonomy level, transferability, metadata and hardware cost remain variable	Accelerates evidence generation; treated as emerging infrastructure
DELIVER translational framework [55]	Preclinical-to-clinical nanomedicine translation	Reproducibility, manufacturing, regulation and development risk	Biomedical-specific and not directly portable to all engineering domains	Illustrates translation-readiness requirements
Safe and Sustainable by Design [32]	Lifecycle-integrated safety and sustainability	Hazard, exposure, resource use and lifecycle trade-offs	Data-intensive; endpoints and thresholds depend on material/use context	Adds safety/lifecycle constraints to translation readiness
Evidence chain in this review	Synthesis control -> verified structure -> active-state mechanism -> functional validation -> translation readiness	Cross-domain traceability from laboratory claim to engineering interpretation	Not a validated universal scoring system; criteria require domain adaptation	Practical integrative framework and checklist for this narrative review

3.5.2. Minimum evidence package for engineering translation. The minimum evidence package turns that sequence into a set of questions rather than a score. Its depth should match the maturity and intended use of the study. Four questions concern scientific traceability: what was controlled in the process, what structure or chemistry was verified, whether the proposed mechanism was tested under relevant conditions, and whether the functional response was measured in a meaningful way. A fifth question concerns translation, but the endpoint cannot be the same for every field. An early fundamental study may reasonably leave manufacturing or regulation untested. The problem arises only when those untested steps are hidden behind claims of technology readiness.

Table 5. Literature-supported minimum evidence package and domain-specific interpretation.

Evidence dimension	Minimum question	Risk if absent	Representative support	Domain adaptation
1. Synthesis / process control	Which controllable variables define the relevant nanostructure, interface, or defect population?	Apparent performance cannot be reproduced or causally attributed to processing.	[48], [49], [50], [34]	Electronics: contact/deposition history; batteries: loading, formulation and processing; colloids: ligands, solvent and batch history.
2. Structural and chemical proof	Are size, phase, morphology, defects, surface/interface chemistry and composition cross-validated by complementary methods?	A single image or spectrum can support an incorrect structural assignment.	[36], [38], [39]	Use methods with non-redundant sensitivities; buried interfaces and heterogeneous systems usually require multimodal evidence.
3. Active-state mechanism	Is the proposed mechanism demonstrated under	The pristine or post-mortem state may be	[38], [40], [42], [44]	Operando is most important when reconstruction or transient intermediates are plausible; stable

Evidence dimension	Minimum question	Risk if absent	Representative support	Domain adaptation
	the relevant bias, reaction, cycling, illumination, thermal, mechanical, or environmental condition?	mistaken for the functional state.		systems may instead require stress/bias/aging validation.
4. Functional validation	Is performance benchmarked with stability, uncertainty, reproducibility and application-relevant conditions?	A peak metric may reflect a favorable but non-robust test condition and overstate engineering significance.	[43], [44], [47], [49]	Metrics differ by domain: EQE/lifetime, contact resistance/yield, capacity/loading/cycle life, sensitivity/selectivity, or catalytic rate/stability.
5. Translation readiness	Which scale-up, manufacturing, recovery, exposure, safety, regulatory or lifecycle constraints are relevant, and which have actually been tested?	Performance may collapse outside the laboratory or create unacceptable cost, safety, exposure, or lifecycle burdens.	[55], [32]	Electronics: wafer/pixel uniformity and process compatibility; batteries: high loading, full-cell format and safety; biomedical: exposure/biocompatibility/regulation; environmental: recovery, leaching and lifecycle.

Used this way, the package is a traceability checklist, not a gatekeeping score. A semiconductor device may need strong evidence on interface fabrication, contact resistance, switching reliability, and process compatibility. A biomedical nanomaterial needs a different depth of evidence on exposure, biocompatibility, manufacturing, and regulatory risk [55]. Environmental systems bring recovery, leaching, transformation, and lifecycle questions to the foreground; batteries require realistic loading, cell architecture, cycling, safety, and failure analysis. What remains common is the standard of claim: the asserted level of readiness should not outrun the least mature part of the evidence.

3.5.3. Evidence maturity and uncertainty. Not every mechanism or methodology discussed in this review is supported at the same level. Some effects, such as size-dependent confinement within its accepted regime or interface-controlled transport, rest on broad experimental convergence. Other mechanisms are well supported but remain architecture- or environment-dependent; active-state reconstruction in many electrochemical systems belongs in this category. Self-driving laboratories and operational SSbD implementation are further upstream in maturity: they have strong proof-of-concept value but less cross-laboratory standardization and fewer long-duration deployment data [34], [32]. The weakest cases are those inferred from a single modality, a specialized test geometry, or conflicting datasets. The language used in the review follows that distinction, separating direct observation from correlation, interpretation, and hypothesis.

4. CONCLUSION

Several conclusions are consistent across the literature. Nanomaterial performance rarely belongs to one variable. Size matters, but so do surface chemistry, defects, phase, interfaces, and process history, often in ways that cannot be separated cleanly. Quantum confinement and surface-dominated behavior are established physical effects, yet their device benefit depends on passivation, interface quality, architecture, and operating environment. Operando studies add another important qualification: in catalytic, electrochemical, sensing, and optoelectronic systems, the structure that carries the function may not be the structure observed before or after operation.

The same literature also explains why strong laboratory results so often weaken during translation. Peak performance can mask unstable interfaces, unrealistic loading, poor reproducibility, or a process that does not survive scale-up. In biomedical and environmental settings, exposure and recovery add constraints that are largely absent from a benchtop metric. These recurring failures argue for multi-objective materials engineering rather than one-variable optimization. They also caution against treating all emerging tools as equally mature. Autonomous laboratories and operational SSbD workflows are promising, but their standardization and deployment evidence still lag behind mature structure-property mechanisms.

The evidence-chain framework proposed here is meant to make those distinctions easier to see. It is not a new fundamental theory and it is not a universal scoring system. Instead, it asks whether a result can be traced from a controlled process to verified structure and chemistry, then to the active-state mechanism and a functional test, before the remaining translation boundary is stated explicitly. The amount of evidence needed at each step should vary with the application. Used in that way, the framework provides a disciplined way to separate a persuasive laboratory result from an engineering claim whose weakest link has already been examined.

REFERENCES

- [1] N. Baig, I. Kammakakam, and W. Falath, "Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges," *Materials Advances*, vol. 2, pp. 1821-1871, 2021, doi: [10.1039/D0MA00807A](https://doi.org/10.1039/D0MA00807A).
- [2] V. Harish et al., "Review on nanoparticles and nanostructured materials: bioimaging, biosensing, drug delivery, tissue engineering, antimicrobial, and agro-food applications," *Nanomaterials*, vol. 12, no. 3, p. 457, 2022, doi: [10.3390/nano12030457](https://doi.org/10.3390/nano12030457).
- [3] A. Sohail, "Progress in nanomaterials: synthesis, characterization, and applications," *Next Nanotechnology*, vol. 8, p. 100263, 2025, doi: [10.1016/j.nxnano.2025.100263](https://doi.org/10.1016/j.nxnano.2025.100263).
- [4] A. Merchant et al., "Scaling deep learning for materials discovery," *Nature*, vol. 624, pp. 80-85, 2023, doi: [10.1038/s41586-023-06735-9](https://doi.org/10.1038/s41586-023-06735-9).
- [5] N. J. Szymanski et al., "An autonomous laboratory for the accelerated synthesis of inorganic materials," *Nature*, vol. 624, pp. 86-91, 2023, doi: [10.1038/s41586-023-06734-w](https://doi.org/10.1038/s41586-023-06734-w).
- [6] M. Otyepka, M. Pykal, and M. Otyepka, "Advancing materials discovery through artificial intelligence," *Applied Materials Today*, vol. 47, p. 102981, 2025, doi: [10.1016/j.apmt.2025.102981](https://doi.org/10.1016/j.apmt.2025.102981).
- [7] X. Bai and X. Zhang, "Artificial Intelligence-Powered Materials Science," *Nano-Micro Letters*, vol. 17, p. 135, 2025, doi: [10.1007/s40820-024-01634-8](https://doi.org/10.1007/s40820-024-01634-8).
- [8] C. Caldeira, E. Abbate, C. Moretti, L. Mancini, and S. Sala, "Safe and sustainable chemicals and materials: a review of sustainability assessment frameworks," *Green Chemistry*, vol. 26, pp. 7456-7477, 2024, doi: [10.1039/D3GC04598F](https://doi.org/10.1039/D3GC04598F).
- [9] A. Kostapanou, K.-R. Chatzipanagiotou, S. Damiros, F. Petrakli, and E. P. Koumoulos, "Safe-and-sustainable-by-design framework: (Re-)designing the advanced materials lifecycle," *Sustainability*, vol. 16, no. 23, p. 10439, 2024, doi: [10.3390/su162310439](https://doi.org/10.3390/su162310439).
- [10] S. Dabare, S. Rajapaksha, and I. Munaweera, "Lifecycle analysis of nanotechnology-enhanced soft materials in the circular economy," *Molecular Systems Design & Engineering*, vol. 10, pp. 799-816, 2025, doi: [10.1039/D5ME00067J](https://doi.org/10.1039/D5ME00067J).
- [11] H. D. Romero-Cantú et al., "Current knowledge for implementing safe and sustainable by design across the life cycle of nanosilver textiles," *Discover Sustainability*, vol. 6, p. 1353, 2025, doi: [10.1007/s43621-025-02092-x](https://doi.org/10.1007/s43621-025-02092-x).
- [12] P. Dhumal, P. Bhadane, B. Ibrahim, and S. Chakraborty, "Evaluating the path to sustainability: SWOT analysis of safe and sustainable by design approaches for metal-organic frameworks," *Green Chemistry*, vol. 27, pp. 3815-3850, 2025, doi: [10.1039/D5GC00424A](https://doi.org/10.1039/D5GC00424A).
- [13] Y. Wang et al., "Patterning technologies of quantum dots for color-conversion micro-LED display applications," *Nanoscale*, vol. 17, pp. 1764-1789, 2025, doi: [10.1039/D4NR03925D](https://doi.org/10.1039/D4NR03925D).
- [14] A. Hassan, J. Kaur, O. Chen, and M. G. Bawendi, "Quantum dots: A journey from fundamental discovery to technological impacts," *MRS Bulletin*, vol. 50, pp. 1439-1453, 2025, doi: [10.1557/s43577-025-01007-5](https://doi.org/10.1557/s43577-025-01007-5).
- [15] A. Taher et al., "Quantum dot-based non-volatile memory: a comprehensive outlook," *RSC Advances*, vol. 15, pp. 14428-14462, 2025, doi: [10.1039/D4RA08307E](https://doi.org/10.1039/D4RA08307E).
- [16] A. Kumar et al., "Integrating green nanotechnology with sustainable development goals: a pathway to sustainable innovation," *Discover Sustainability*, vol. 5, p. 364, 2024, doi: [10.1007/s43621-024-00610-x](https://doi.org/10.1007/s43621-024-00610-x).
- [17] A. I. Osman et al., "Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review," *Environmental Chemistry Letters*, vol. 22, no. 2, pp. 841-887, 2024, doi: [10.1007/s10311-023-01682-3](https://doi.org/10.1007/s10311-023-01682-3).
- [18] S. Chakraborty, S. K. Misra, J. R. Lead, and I. Lynch, "Capturing rapid nanomaterial transformations with cross-platform operando characterization," *Nature Reviews Materials*, vol. 11, pp. 346-348, 2026, doi: [10.1038/s41578-025-00844-9](https://doi.org/10.1038/s41578-025-00844-9).

- [19] O. O. Barah, M. David, and M. Joseph, "Atomic-scale characterization: a review of advances in microscopy, spectroscopy, and machine learning," *Journal of Materials Science: Composites*, vol. 6, p. 6, 2025, doi: [10.1186/s42252-025-00073-x](https://doi.org/10.1186/s42252-025-00073-x).
- [20] M. A. Islam et al., "Recent advances of 2D materials in semiconductor application: A review," *Advanced Sensor and Energy Materials*, vol. 4, no. 4, p. 100161, 2025, doi: [10.1016/j.asems.2025.100161](https://doi.org/10.1016/j.asems.2025.100161).
- [21] N. Farooq et al., "Nanomaterial-based energy conversion and energy storage devices: a comprehensive review," *New Journal of Chemistry*, vol. 48, pp. 8933-8962, 2024, doi: [10.1039/D3NJ04846B](https://doi.org/10.1039/D3NJ04846B).
- [22] J. Meena, S. S. Sivasubramaniam, E. David, and S. K., "Green supercapacitors: review and perspectives on sustainable template-free synthesis of metal and metal oxide nanoparticles," *RSC Sustainability*, vol. 2, pp. 1224-1245, 2024, doi: [10.1039/D4SU00009A](https://doi.org/10.1039/D4SU00009A).
- [23] L. Li et al., "A review of nanomaterials for biosensing applications," *Journal of Materials Chemistry B*, vol. 12, pp. 1168-1193, 2024, doi: [10.1039/D3TB02648E](https://doi.org/10.1039/D3TB02648E).
- [24] F. Kurul, H. Turkmen, A. E. Cetin, and S. N. Topkaya, "Nanomedicine: How nanomaterials are transforming drug delivery, bio-imaging, and diagnosis," *Next Nanotechnology*, vol. 7, p. 100129, 2025, doi: [10.1016/j.nxnano.2024.100129](https://doi.org/10.1016/j.nxnano.2024.100129).
- [25] O. Zakir et al., "Recent progress in nanomaterials for water treatment: A comprehensive review of adsorption, photocatalytic, and antibacterial applications," *Journal of Water Process Engineering*, vol. 72, p. 107566, 2025, doi: [10.1016/j.jwpe.2025.107566](https://doi.org/10.1016/j.jwpe.2025.107566).
- [26] S. Shahzadi et al., "A review on green synthesis of silver nanoparticles (SNPs) using plant extracts: a multifaceted approach in photocatalysis, environmental remediation, and biomedicine," *RSC Advances*, vol. 15, pp. 3858-3903, 2025, doi: [10.1039/D4RA07519F](https://doi.org/10.1039/D4RA07519F).
- [27] I. A. Tasiu et al., "Spintronics technology: A comprehensive review of materials, applications, and future trends," *Journal of Science: Advanced Materials and Devices*, vol. 11, no. 1, p. 101087, 2026, doi: [10.1016/j.jsamd.2025.101087](https://doi.org/10.1016/j.jsamd.2025.101087).
- [28] C. Baethge, S. Goldbeck-Wood, and S. Mertens, "SANRA—a scale for the quality assessment of narrative review articles," *Research Integrity and Peer Review*, vol. 4, p. 5, 2019, doi: [10.1186/s41073-019-0064-8](https://doi.org/10.1186/s41073-019-0064-8).
- [29] M. L. Rethlefsen et al., "PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews," *Systematic Reviews*, vol. 10, p. 39, 2021, doi: [10.1186/s13643-020-01542-z](https://doi.org/10.1186/s13643-020-01542-z).
- [30] M. A. VandenBerg et al., "Learning from the future: towards continuous manufacturing of nanomaterials," *AAPS Open*, vol. 11, p. 7, 2025, doi: [10.1186/s41120-025-00111-9](https://doi.org/10.1186/s41120-025-00111-9).
- [31] E. O. Atofarati, P. O. Oviroh, O. Folorunso, and T. C. Jen, "Emerging applications and trends in atomic layer deposition nano-coatings," *Journal of Coatings Technology and Research*, vol. 23, pp. 229-254, 2026, doi: [10.1007/s11998-025-01154-z](https://doi.org/10.1007/s11998-025-01154-z).
- [32] F. Pitaro, S. Seeger, and B. Nowack, "The safe and sustainable by design framework applied to graphene-based materials," *Environment International*, vol. 197, p. 109345, 2025, doi: [10.1016/j.envint.2025.109345](https://doi.org/10.1016/j.envint.2025.109345).
- [33] T. Ohno, J. K. Padarti, S. Hirai, and T. Matsuda, "Effects of coating layer homogeneity of cathode particles on lithium ion battery performance," *Advanced Powder Technology*, vol. 35, no. 9, p. 104608, 2024, doi: [10.1016/j.apt.2024.104608](https://doi.org/10.1016/j.apt.2024.104608).
- [34] G. Tom et al., "Self-Driving Laboratories for Chemistry and Materials Science," *Chemical Reviews*, vol. 124, no. 16, pp. 9633-9732, 2024, doi: [10.1021/acs.chemrev.4c00055](https://doi.org/10.1021/acs.chemrev.4c00055).
- [35] A. Thapa and H. Gao, "High Areal Loading Silicon Nanoparticle-Based Lithium-Ion Batteries," *ACS Applied Materials & Interfaces*, vol. 17, no. 6, pp. 9219-9230, 2025, doi: [10.1021/acsami.4c17483](https://doi.org/10.1021/acsami.4c17483).
- [36] M. A. Smeaton, P. Abellan, and S. R. Spurgeon, "Tutorial on In Situ and Operando (Scanning) Transmission Electron Microscopy for Analysis of Nanoscale Structure-Property Relationships," *ACS Nano*, vol. 18, no. 52, pp. 35091-35103, 2024, doi: [10.1021/acsnano.4c09256](https://doi.org/10.1021/acsnano.4c09256).
- [37] Y. Han et al., "In Situ TEM Characterization and Modulation for Phase Engineering of Nanomaterials," *Chemical Reviews*, vol. 123, no. 24, pp. 14119-14184, 2023, doi: [10.1021/acs.chemrev.3c00510](https://doi.org/10.1021/acs.chemrev.3c00510).
- [38] J. T. Mefford et al., "Correlative operando microscopy of oxygen evolution electrocatalysts," *Nature*, vol. 593, pp. 67-73, 2021, doi: [10.1038/s41586-021-03454-x](https://doi.org/10.1038/s41586-021-03454-x).
- [39] Y. Yang et al., "Dynamic Evolution of Copper Nanowires during CO₂ Reduction Probed by Operando Electrochemical 4D-STEM and X-ray Spectroscopy," *Journal of the American Chemical Society*, vol. 146, no. 33, pp. 23398-23405, 2024, doi: [10.1021/jacs.4c06480](https://doi.org/10.1021/jacs.4c06480).

- [40] Y. Zhang et al., "Operando characterization and regulation of metal dissolution and redeposition dynamics near battery electrode surface," *Nature Nanotechnology*, vol. 18, pp. 790-797, 2023, doi: [10.1038/s41565-023-01367-6](https://doi.org/10.1038/s41565-023-01367-6).
- [41] S. Lang et al., "Understanding the lithium-sulfur battery redox reactions via operando confocal Raman microscopy," *Nature Communications*, vol. 13, p. 4811, 2022, doi: [10.1038/s41467-022-32139-w](https://doi.org/10.1038/s41467-022-32139-w).
- [42] F. G. Capone et al., "Operando observation of the dynamic SEI formation on a carbonaceous electrode by near-ambient pressure XPS," *Energy & Environmental Science*, vol. 17, pp. 1509-1519, 2024, doi: [10.1039/D3EE03228K](https://doi.org/10.1039/D3EE03228K).
- [43] M. Scardamaglia et al., "Operando Investigation of WS₂ Gas Sensors: Simultaneous Ambient Pressure X-ray Photoelectron Spectroscopy and Electrical Characterization in Unveiling Sensing Mechanisms during Toxic Gas Exposure," *ACS Sensors*, vol. 9, no. 8, pp. 4079-4088, 2024, doi: [10.1021/acssensors.4c01033](https://doi.org/10.1021/acssensors.4c01033).
- [44] S. Wang et al., "Operando ZnO recrystallization for efficient quantum-dot light-emitting diodes," *Light: Science & Applications*, vol. 14, p. 196, 2025, doi: [10.1038/s41377-025-01867-1](https://doi.org/10.1038/s41377-025-01867-1).
- [45] R. X. Yang et al., "Big Data in a Nano World: A Review on Computational, Data-Driven Design of Nanomaterials Structures, Properties, and Synthesis," *ACS Nano*, vol. 16, no. 12, pp. 19873-19891, 2022, doi: [10.1021/acsnano.2c08411](https://doi.org/10.1021/acsnano.2c08411).
- [46] P. Muhammad et al., "Defect Engineering in Nanocatalysts: From Design and Synthesis to Applications," *Advanced Functional Materials*, vol. 34, no. 29, p. 2314686, 2024, doi: [10.1002/adfm.202314686](https://doi.org/10.1002/adfm.202314686).
- [47] B. Li et al., "Advances in understanding quantum dot light-emitting diodes," *Nature Reviews Electrical Engineering*, vol. 1, pp. 412-425, 2024, doi: [10.1038/s44287-024-00059-0](https://doi.org/10.1038/s44287-024-00059-0).
- [48] Y. Xu, M. Lyu, and J. Zhu, "Surface engineering in CsPbX₃ quantum dots: from materials to solar cells," *Materials Chemistry Frontiers*, vol. 8, no. 9, pp. 2029-2055, 2024, doi: [10.1039/D3QM00911D](https://doi.org/10.1039/D3QM00911D).
- [49] Y. Wang et al., "Critical challenges in the development of electronics based on two-dimensional transition metal dichalcogenides," *Nature Electronics*, vol. 7, pp. 638-645, 2024, doi: [10.1038/s41928-024-01210-3](https://doi.org/10.1038/s41928-024-01210-3).
- [50] X. Liu et al., "Contact resistance and interfacial engineering: Advances in high-performance 2D-TMD based devices," *Progress in Materials Science*, vol. 148, p. 101390, 2025, doi: [10.1016/j.pmatsci.2024.101390](https://doi.org/10.1016/j.pmatsci.2024.101390).
- [51] M. Dong, Y. Sun, D. J. Dunstan, R. J. Young, and D. G. Papageorgiou, "Mechanical reinforcement from two-dimensional nanofillers: model, bulk and hybrid polymer nanocomposites," *Nanoscale*, vol. 16, pp. 13247-13299, 2024, doi: [10.1039/D4NR01356E](https://doi.org/10.1039/D4NR01356E).
- [52] Y. Yan et al., "Bridging the Thermal Divide: Nano-Architectonics and Interface Engineering Strategies for High-Performance 2D Material-Based Polymer Composites," *ACS Nano*, vol. 19, no. 22, pp. 20357-20402, 2025, doi: [10.1021/acsnano.5c02539](https://doi.org/10.1021/acsnano.5c02539).
- [53] A. Giri et al., "Ultrafast and Nanoscale Energy Transduction Mechanisms and Coupled Thermal Transport across Interfaces," *ACS Nano*, vol. 17, no. 15, pp. 14253-14282, 2023, doi: [10.1021/acsnano.3c02417](https://doi.org/10.1021/acsnano.3c02417).
- [54] P. Yapa, S. Rajapaksha, and I. Munaweera, "The integration of nanotechnology, nanomedicine, and artificial intelligence for advancements in healthcare: A conceptual review based on PRISMA method and future research directions," *Next Research*, vol. 2, no. 2, p. 100330, 2025, doi: [10.1016/j.nexres.2025.100330](https://doi.org/10.1016/j.nexres.2025.100330).
- [55] P. Joyce et al., "A translational framework to DELIVER nanomedicines to the clinic," *Nature Nanotechnology*, vol. 19, pp. 1597-1611, 2024, doi: [10.1038/s41565-024-01754-7](https://doi.org/10.1038/s41565-024-01754-7).
- [56] P. Das, L. Biswal, and K. Parida, "A review on MXene modified quantum dot photocatalysts for sustainable energy generation and environmental remediation," *Catalysis Science & Technology*, vol. 15, pp. 6976-7003, 2025, doi: [10.1039/D5CY00606F](https://doi.org/10.1039/D5CY00606F).
- [57] S. Kuehr et al., "Reduced bioavailability of Au and isotopically enriched ¹⁰⁹Ag nanoparticles transformed through a pilot wastewater treatment plant in *Hyalella azteca* under environmentally relevant exposure scenarios," *Science of the Total Environment*, vol. 949, p. 174768, 2024, doi: [10.1016/j.scitotenv.2024.174768](https://doi.org/10.1016/j.scitotenv.2024.174768).
- [58] D. C. Worledge and G. Hu, "Spin-transfer torque magnetoresistive random access memory technology status and future directions," *Nature Reviews Electrical Engineering*, vol. 1, pp. 730-747, 2024, doi: [10.1038/s44287-024-00111-z](https://doi.org/10.1038/s44287-024-00111-z).
- [59] R. Arróyave and D. L. McDowell, "Systems Approaches to Materials Design: Past, Present, and Future," *Annual Review of Materials Research*, vol. 49, pp. 103-126, 2019, doi: [10.1146/annurev-matsci-070218-125955](https://doi.org/10.1146/annurev-matsci-070218-125955).
- [60] S. M. Hashemi et al., "Computational modelling of process-structure-property-performance relationships in metal additive manufacturing: a review," *International Materials Reviews*, vol. 67, no. 1, pp. 1-46, 2022, doi: [10.1080/09506608.2020.1868889](https://doi.org/10.1080/09506608.2020.1868889).