

**LITERATURE REVIEW AND QUALITATIVE ANALYSIS OF NANOMATERIAL RESEARCH TRENDS IN ENVIRONMENTAL APPLICATIONS (2015–2025)**Kinley Dorji<sup>1</sup>, Sahar Yazdani<sup>2</sup>, and Ali Akbar<sup>3</sup><sup>1</sup> College of Science and Technology, Royal University of Bhutan, Rinchending, Bhutan<sup>2</sup> Iran University of Science and Technology, Tehran, Iran<sup>3</sup> University of Science and Technology, Tehran, Iran**Corresponding Author:**

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**Abstract**

Over the past decade (2015–2025), research on nanomaterials for environmental applications has accelerated, spanning water and wastewater treatment, air pollution mitigation, soil remediation, sensing and monitoring, and circular economy approaches; this paper provides a structured literature review combined with a qualitative analysis of publication trends, dominant technologies, translational challenges, and research gaps. We synthesized peer-reviewed reviews, meta-analyses, and recent empirical studies (2020–2025) to identify dominant material classes (carbon-based materials, metal/metal-oxide nanoparticles, nanocomposites, and photocatalysts), prevalent mechanisms (adsorption, catalysis, membrane augmentation, and sensing transduction), and evolving priorities such as green/biogenic synthesis, life-cycle impacts, and governance of engineered nanomaterials. The analysis highlights a growing emphasis on scalable, low-cost water-treatment solutions, nano-enabled sensors for environmental monitoring, and hybrid materials that combine high reactivity with stability; concurrently, concerns about environmental fate, ecotoxicity, predictable exposure, and end-of-life management have prompted methodological refinement in exposure modeling and standardized testing. We conclude with a qualitative roadmap recommending integrated techno-ecological assessments, standardized exposure frameworks, upscaling pathways, and stronger transdisciplinary collaborations to translate laboratory innovations into safe, equitable environmental technologies.

**Keywords:** Environmental Applications, Literature Review, Nanomaterials

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## INTRODUCTION

Nanomaterials — broadly defined as materials with structural features at the nanoscale that confer distinctive physical, chemical, or biological properties — have been investigated intensively for environmental applications due to their high surface area, tunable reactivity, and multifunctionality, enabling processes such as adsorption of contaminants, photocatalytic degradation of organics, catalytic reduction of pollutants, and sensitive transduction in sensors; this surge in research is evident across disciplines and geographies from 2015 through 2025. (Altammar, 2023).

Among the early application areas, water and wastewater treatment have dominated both academic and applied research agendas, where nanomaterials — including nanoscale zero-valent iron (nZVI), metal-oxide nanoparticles, carbon nanotubes, graphene derivatives, and nanocomposite membranes — have been engineered to remove heavy metals, pathogens, organic micropollutants, and persistent contaminants more efficiently than many conventional technologies. (Elhenawy, 2024).

Parallel to water treatment, air pollution control and catalysis have embraced nanomaterials for gas-phase adsorption, catalytic oxidation of volatile organics, and the design of photocatalytic coatings that degrade airborne contaminants, with increasing attention to operational stability under real-world environmental conditions. (Saleem, 2022). Soil remediation is another emergent frontier where nano-enabled strategies — such as iron-based nanoparticles for dechlorination or nano-adsorbents for immobilizing heavy metals — are being trialed, prompting debates about subsurface transport, long-term immobilization, and unintended ecological exposure. (Wang, 2025).

The last five years (2020–2025) show a clear pivot towards multifunctional, hybrid nanomaterials that combine adsorption with catalytic activity or sensing with remediation (e.g., photocatalyst–adsorbent composites), motivated by the need to treat mixed pollutant streams and deliver real-time performance feedback in field deployments. (Asghar, 2024). At the same time, the field has seen a methodological maturation: studies increasingly integrate life-cycle thinking, eco-toxicological assays, and predictive exposure modeling to assess environmental risks and to inform safer-by-design approaches, responding to policy and public concerns about engineered nanomaterial release and persistence. (Keller, 2024).

Another notable trend is the growth of green and biogenic synthesis routes for nanomaterials — using plant extracts, microbes, or benign precursors — to reduce hazardous reagents and produce materials with improved biocompatibility, which aligns with the broader sustainability goals in environmental engineering. (Nakum, 2022). Research on nano-enabled environmental sensors has expanded rapidly as well, with advances in nanomaterial-based transducers (graphene, metal-organic frameworks, noble metal nanoparticle catalysts) enabling lower detection limits, multiplexing, and integration with portable electronics and IoT networks for environmental monitoring. (Ramesh, 2022).

Despite these advances, translational gaps persist: scaling lab-proven nanomaterials to economically viable, robust field systems remains arduous, and standardized protocols for environmental fate, toxicity, and exposure quantification are still developing, which slows regulatory acceptance and industrial uptake. (Bradford, 2022). Given the accelerating pace of publications and the wide diversity of materials and application niches, this paper conducts a

structured literature review (with emphasis on 2020–2025) and a qualitative trend analysis to map the state of the art, identify persistent research and regulatory gaps, and propose directions for research and policy to responsibly harness nanomaterials for environmental applications. (Asghar, 2024).

## RESEARCH METHOD

We carried out a systematic literature mapping of peer-reviewed articles, reviews, and authoritative reports published between 2015 and 2025 with focused in-depth synthesis on 2020–2025 works to capture the latest methodological and application trends; databases searched included Web of Science, Scopus, PubMed, and Google Scholar using combinations of keywords such as “nanomaterial”, “environmental remediation”, “water treatment”, “air pollution”, “soil remediation”, and “nano-sensors”. (Asghar, 2024).

Inclusion criteria prioritized (a) review articles and meta-analyses that synthesized multiple primary studies, (b) empirical studies with field or pilot-scale validations, (c) works addressing environmental fate/exposure, and (d) methodological papers on ecotoxicology or life-cycle assessment of nanomaterials; exclusion criteria removed purely medical or biomedical nanomaterial studies unless they had direct environmental relevance. (Bradford, 2022).

For trend and thematic analysis, we combined bibliometric indicators (publication counts by year, keyword co-occurrence) with qualitative coding: a purposive sample of ~120 highly cited and/or recent papers (2020–2025) was read in full and coded for material class, application domain, performance metrics, scale (lab/pilot/field), toxicity/fate assessments, and translational barriers. (Kumar, 2023). To interpret thematic patterns beyond bibliometrics, the study employed a narrative synthesis and inductive thematic analysis approach (coding in NVivo), triangulating findings with authoritative review articles and recent policy-oriented reports to build a holistic view of technological trajectories and societal concerns. (Ramesh, 2022).

Additionally, we performed mini case syntheses of representative subfields — e.g., graphene-based membranes for desalination, photocatalytic nanostructures for micropollutant degradation, and nano-enabled sensors for volatile organic compound detection — to illustrate technical progress, real-world constraints, and safety considerations. (Abbas, 2022). Limitations of the methods include potential selection bias toward English-language publications and toward studies that report positive performance metrics; we mitigate these by explicitly searching for negative results, methodological critiques, and risk-assessment literature to ensure balanced interpretation. (Keller, 2024)..

## RESULTS AND DISCUSSION

Bibliometric trends show a steady increase in annual publications on environmental nanomaterials from 2015 through 2024, with a sharper rise after 2019 reflecting both technological maturation and policy interest in sustainable remediation solutions; within 2020–2025, review articles proliferated, indicating consolidation and reflexive evaluation of the field. (Asghar, 2024). Carbon-based materials (graphene, graphene oxide, carbon nanotubes, biochar-derived nanocarbon) have been especially prominent due to exceptional adsorptive capacity, electrical conductivity (beneficial for sensor platforms), and tunable surface chemistries that facilitate composite formation with catalytic nanoparticles. (Abbas, 2022).

Metal and metal-oxide nanoparticles (e.g., nanoscale zero-valent iron, TiO<sub>2</sub>, ZnO, Fe<sub>3</sub>O<sub>4</sub>) continue to be widely studied for redox-based remediation and photocatalysis, with iterative improvements in doping, morphology control, and immobilization on supports to reduce aggregation and leaching. (Saleem, 2022). Hybrid nanocomposites that marry adsorptive

phases with photocatalytic or magnetic separation functionalities emerged as a major trend, aiming to combine fast capture, catalytic breakdown of organics, and facile recovery — a combination that addresses common criticisms about recoverability and secondary contamination. (Asghar, 2024).

Photocatalytic nanomaterials retained strong attention, with efforts to shift activation wavelengths toward visible light, reduce recombination via heterojunction engineering, and integrate photocatalysts into membranes and coatings for continuous-flow treatment systems. (Zhang, 2024). Membrane technologies enhanced by nanomaterials — nanoparticle-infused ultrafiltration and composite reverse-osmosis membranes — were widely investigated to improve fouling resistance, permeability, and selectivity, though concerns about nanoparticle leaching and long-term stability remain salient. (Elhenawy, 2024).

Nano-enabled sensors constituted a rapidly expanding subfield, where nanomaterials enhanced sensitivity, selectivity, and miniaturization for detection of heavy metals, organics, and gaseous pollutants; integration with portable electronics and wireless networks suggested near-term prospects for distributed environmental monitoring. (Ramesh, 2022). Green synthesis approaches rose in prominence as researchers pursued environmentally benign production routes using plant extracts, biopolymers, and microbial templates that can lower toxic reagent use and sometimes confer functionalized surfaces beneficial for specific environmental interactions. (Nakum, 2022).

In soil and subsurface applications, nZVI and functionalized iron nanoparticles showed promise for in situ dechlorination and contaminant immobilization, yet field trials highlighted challenges in transport through heterogeneous media and concerns about long-term transformation products. (Wang, 2025). Life-cycle assessment (LCA) and ecotoxicological testing are increasingly incorporated into studies, revealing that while many nanomaterial treatments reduce operational energy or chemical demands, potential upstream impacts (synthesis energy, precursor toxicity) and downstream nanoparticle release can offset some sustainability gains if not properly managed. (Keller, 2024).

Ecotoxicity evidence is mixed: acute laboratory assays demonstrate dose-dependent toxic effects for some nanoparticle classes on sentinel organisms, but environmental relevance depends on realistic exposure concentrations, those concentrations' persistence, and transformations (dissolution, agglomeration, surface aging). This complexity motivates improved environmental fate modeling and standard exposure scenarios. (Zhao, 2021).

Predictive exposure modeling advanced in 2021–2024, with efforts to estimate environmental concentrations (PECs) and to link PECs with hazard data to improve risk characterization; nevertheless, data gaps in release rates from engineered systems and degradation kinetics limit confidence in many risk assessments. (Keller, 2024).

Field and pilot demonstrations remain fewer than laboratory studies but are increasing; successful translational examples often combine low-cost materials (biochar composites, iron-based particles) with simple deployment strategies and local stakeholder engagement, underscoring socioeconomic context as a key determinant of uptake. (Sathish, 2024). Regulatory considerations are shaping research priorities: concerns about nanowaste management, monitoring of incidental release, and standardization of analytical methods have pushed the community to propose standardized testing batteries and reporting templates to support regulation and public confidence. (Bradford, 2022).

An emerging meta-theme is coupling remediation with resource recovery or circularity — for example, adsorption materials that are regenerated and used as fuel or soil amendments — yet rigorous evaluation of net environmental benefits and contaminant fate in such reuse pathways remains limited. (Sol-Magdaleno, 2025). Cost and scalability remain persistent bottlenecks: many high-performing nanomaterials rely on complex synthesis or scarce precursors, and economic analyses that include synthesis, deployment, maintenance, and end-

of-life treatment are still relatively uncommon but necessary for real-world adoption. (Kumar, 2023).

Safety-by-design and eco-design concepts are gaining traction: researchers increasingly explore surface functionalization to minimize bioavailability while preserving performance, and emphasize degradable or recoverable architectures to reduce long-term environmental loading. (Takhar, 2025). Cross-cutting methodological gaps include the need for (a) harmonized ecotoxicology protocols spanning multi-trophic levels, (b) standardized methods for nanoparticle quantification in complex matrices, (c) validated release and transformation rate data for exposure models, and (d) longitudinal field studies that link short-term performance to long-term environmental outcomes; addressing these gaps is essential for safe and effective translation of nanomaterials into environmental technologies. (Keller, 2024).

## CONCLUSION

The literature from 2015 to 2025 demonstrates robust innovation in nanomaterials for environmental applications, with marked growth in multifunctional composites, green synthesis, nano-enabled sensors, and an expanding suite of pilot demonstrations that begin to bridge lab-to-field gaps. (Asghar, 2024). However, scaling and societal deployment require parallel advances in exposure characterization, standardized ecotoxicological testing, cost-effective synthesis, and governance frameworks that address end-of-life management and potential environmental release, implying that technical advances alone are insufficient without integrated sustainability assessment. (Bradford, 2022).

We recommend future research emphasize (a) harmonized testing and reporting standards to enable cross-study comparability, (b) field-scale and longitudinal studies that capture transformation and fate, (c) design-for-recovery strategies that facilitate material reuse without secondary contamination, and (d) multidisciplinary collaborations that pair material scientists with ecotoxicologists, economists, and regulators. (Keller, 2024).

By aligning material innovation with rigorous environmental assessment and pragmatic upscaling strategies, the field can responsibly harness nanomaterials' unique capabilities to deliver durable, equitable solutions to complex environmental challenges in the coming decade. (Wang, 2025).

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