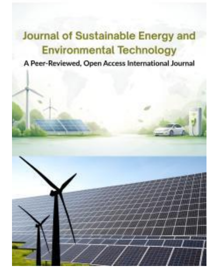
Journal of Sustainable Energy and Environmental Technology

E-ISSN: 3122-0630
P-ISSN: 3121-9454

Volume 2, Issue 1, March, 2026
(An Academians Publishers of Research & Academic Resources)



Review Article

The Remediation Paradox: Engineered Nanomaterials, Emerging Contaminants, and the Sustainability of Advanced Environmental Cleanup

Seera Ramkya*[1], Ismail Guru[2], Nikah Firdos[2]
[1]*National University of Singapore (NUS), Singapore*
[2]*Department of Environmental Engineering, University of Technology – Iraq*

Abstract: The proliferation of engineered nanomaterials for environmental remediation represents one of the most promising yet underexamined frontiers of sustainability science. From nano-biochar adsorbents capable of capturing heavy metals and emerging organic contaminants to photocatalytic systems that generate clean hydrogen while degrading pollutants, advanced materials offer unprecedented tools for addressing environmental degradation. Yet the same properties that make these materials effective—high surface area, reactivity, and persistence—also raise concerns about their own environmental fate, toxicity, and long-term sustainability. This article examines the remediation paradox: the tension between the promise of engineered nanomaterials for contaminant removal and the environmental risks their production, use, and disposal may generate. Drawing on recent advances in nano-biochar synthesis, photocatalytic hydrogen production, and tire-derived contaminant research, the analysis develops an integrated assessment framework identifying four critical dimensions—efficacy, environmental fate, life-cycle performance, and scalability—that must be evaluated together rather than in isolation. The article argues that sustainable remediation requires moving beyond material-centric optimization to embrace systemic assessment that accounts for trade-offs across environmental media, temporal scales, and stakeholder interests. Case analyses of 6PPD-quinone contamination, photocatalytic water splitting, and functionalized nano-biochar illustrate how this framework applies in practice, revealing both the potential and the limitations of current approaches. The analysis concludes by proposing research and policy priorities for advancing remediation technologies that are not only effective but also environmentally sound, economically viable, and socially equitable.

Keywords: *environmental remediation, engineered nanomaterials, nano-biochar, photocatalysis, emerging contaminants, sustainability assessment, life cycle analysis*

1. Introduction

The global burden of environmental contamination continues to grow despite decades of regulatory effort and technological innovation. Industrial chemicals, agricultural runoff, pharmaceutical residues, microplastics, and tire-derived compounds represent just a subset of the thousands of substances that now circulate through air, water, and soil systems, with consequences for ecosystem health and human well-being that are only beginning to be understood (Dunlap et al., 2025; Scott & Smith, 2017). Traditional remediation approaches—excavation, pump-and-treat, thermal desorption, and chemical oxidation—have achieved notable successes at contaminated sites but often prove costly, energy-intensive, and limited in their capacity to address diffuse pollution at landscape scales.

In response to these limitations, attention has increasingly turned to engineered nanomaterials as next-generation remediation tools. Carbon-based materials such as biochar and its nano-structured derivatives offer exceptional adsorption capacities for heavy metals and organic pollutants, with the added benefit of being produced from waste biomass through thermochemical conversion (Pathak et al., 2024). Photocatalytic materials—semiconductors capable of generating reactive oxygen species under illumination—can degrade recalcitrant organic contaminants while simultaneously producing hydrogen as a clean energy carrier (Huang et al., 2025). These and other advanced materials promise remediation that is more efficient,

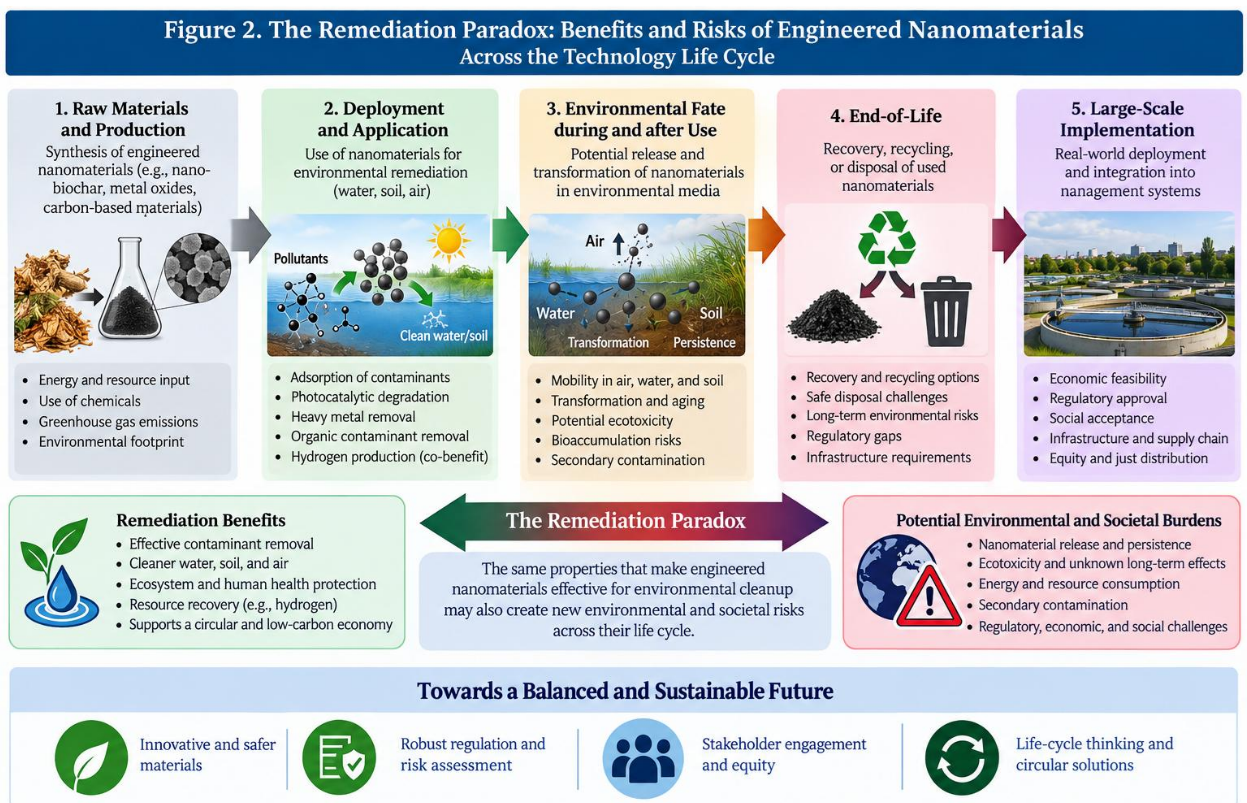
Received 12 January, 2026; Accepted 18 February, 2026; Available Online: 28 March, 2026
Corresponding Author: Seera Ramkya

more versatile, and potentially more sustainable than conventional approaches.

Yet this promise carries an underappreciated tension. The very properties that make engineered nanomaterials effective for contaminant capture—high surface area, reactivity, colloidal stability, and persistence—also determine their behavior when they inevitably enter the environment. Nanoparticles may themselves become contaminants, with toxicity profiles that differ from their bulk counterparts and environmental fates that are difficult to predict or control (Wang et al., 2025). The production of advanced materials requires energy, chemicals, and raw materials, generating environmental burdens that may offset the benefits of remediation. And the deployment of novel technologies at scale raises questions about unintended consequences, regulatory oversight, and distributive justice that cannot be resolved through technical optimization alone.

This article examines what might be called the remediation paradox: the tension between the promise of engineered nanomaterials for environmental cleanup and the environmental risks their production, use, and disposal may generate. The analysis draws on recent research advances in three interconnected domains—nano-biochar synthesis and application, photocatalytic systems for water treatment and hydrogen production, and the emerging challenge of tire-derived contaminants—to develop an integrated framework for assessing remediation technologies. The central argument is that sustainable remediation requires moving beyond material-centric optimization to embrace systemic assessment that accounts for trade-offs across environmental media, temporal scales, and stakeholder interests.

Figure 2. The remediation paradox: balancing contaminant removal benefits against environmental and sustainability burdens across the technology life cycle.



2. The Rise of Engineered Nanomaterials for Remediation

2.1 Nano-Biochar: From Waste to Resource

Biochar—the carbon-rich solid produced by pyrolysis of biomass under limited oxygen—has been recognized for centuries as a soil amendment capable of improving fertility, water retention, and carbon sequestration. More recently, researchers have discovered that engineering biochar at the nanoscale dramatically enhances its adsorptive properties, creating materials with surface areas hundreds of times greater than conventional biochar and functional groups that can be tailored to specific contaminant classes (Pathak et al., 2024).

The production of nano-biochar typically involves ball milling—a mechanical process that reduces bulk biochar to particles ranging from tens to hundreds of nanometers.

This physical transformation increases external surface area, exposes previously inaccessible internal pores, and creates edge sites with enhanced reactivity. The resulting material exhibits adsorption capacities for heavy metals that far exceed those of unmodified biochar. For lead, for example, maximum adsorption capacities ranging from 55 to over 180 milligrams per gram have been reported for various nano-biochar formulations, compared to 6 to 57 milligrams per gram for bulk biochars (Pathak et al., 2024).

Chemical functionalization further expands the range of contaminants that nano-biochar can capture. Nitrogen doping enhances the material's affinity for heavy metals through complexation and electrostatic interactions. Loading with iron or manganese oxides creates sites for arsenic and phosphate adsorption. Magnetic modification—typically through incorporation of Fe_3O_4 nanoparticles—enables easy recovery of spent adsorbent from aqueous solution using an external magnetic field. These modifications transform nano-biochar from a generic adsorbent into a tunable platform that can be engineered for specific remediation challenges.

The feedstock for nano-biochar production encompasses the full spectrum of waste biomass: agricultural residues, forestry waste, food processing byproducts, sewage sludge, and animal manures. This diversity is both an advantage and a complication. It enables local production using readily available materials, reducing transportation costs and supporting circular economy principles. However, it also means that biochar properties—and therefore remediation performance—vary with feedstock composition, pyrolysis conditions, and modification procedures in ways that are not always predictable or controllable.

2.2 Photocatalytic Materials for Water Treatment and Energy Production

Photocatalysis offers a fundamentally different approach to remediation. Rather than capturing and concentrating contaminants, photocatalytic materials generate reactive oxygen species—hydroxyl radicals, superoxide anions, and hydrogen peroxide—that oxidize organic pollutants to less harmful products, potentially achieving complete mineralization to carbon dioxide and water (Huang et al., 2025). This destructive mechanism avoids the need for adsorbent regeneration or disposal, addressing one of the key limitations of adsorption-based approaches.

The most widely studied photocatalytic material is titanium dioxide, which has been used for decades in self-cleaning surfaces, air purification, and water treatment. However, titanium dioxide's wide bandgap limits its activity to the ultraviolet portion of the solar spectrum, which constitutes only about four percent of incident solar radiation. This limitation has driven the development of visible-light-active photocatalysts, including doped titanium dioxide, bismuth-based semiconductors, and carbon nitride materials.

More recently, researchers have explored photocatalytic systems that simultaneously degrade pollutants and produce hydrogen—a dual-function approach that addresses both environmental remediation and clean energy generation. Strontium titanate modified with rhodium, cobalt, and chromium co-catalysts has demonstrated promising performance for overall water splitting, achieving solar-to-hydrogen efficiencies that, while still low, suggest the feasibility of scalable systems (Huang et al., 2025). The integration of pollutant degradation with hydrogen production creates a potentially self-sustaining remediation system: the energy carrier produced during treatment can be used to power the treatment process or exported for other uses.

Yet photocatalytic systems face their own challenges. The efficiency of solar energy conversion remains low, typically less than one percent for overall water splitting under ambient conditions. Catalyst stability over extended operation is a concern, particularly for materials containing precious metals or complex multi-component structures. And the scale-up from laboratory demonstrations to industrial systems involves engineering challenges—reactor design, light distribution, mass transfer—that are not resolved by advances in materials science alone.

3. Emerging Contaminants and the Limits of Current Approaches

3.1 The 6PPD-Quinone Problem

The discovery of 6PPD-quinone—a transformation product of the tire antiozonant 6PPD—illustrates both the scale of emerging contaminant challenges and the limitations of current remediation paradigms. 6PPD has been added to tires for decades to prevent degradation by ozone, extending tire life and improving safety. When tires wear, 6PPD is released to road surfaces and subsequently transformed by reaction with ozone to 6PPD-quinone, a compound that has proven acutely toxic to certain fish species at concentrations as low as tens of nanograms per liter (Gu et al., 2025).

The environmental ubiquity of 6PPD-quinone reflects the scale of tire production and use worldwide. Tire wear particles are generated continuously during vehicle operation, accumulating on roads, in stormwater runoff, and ultimately in receiving waters. The compound has been detected in urban rivers, estuaries, and coastal waters across North America, Europe, Asia, and Australia, with concentrations frequently exceeding toxicity thresholds for sensitive species (Gu et al., 2025). For coho salmon in the Pacific Northwest, exposure to urban runoff containing 6PPD-quinone causes mortality rates approaching one hundred percent, contributing to population declines that have been documented for decades but only recently attributed to this specific chemical.

6PPD-quinone exemplifies the characteristics of emerging contaminants that make them difficult to address through conventional approaches. It is not a deliberately produced chemical but a transformation product, meaning that regulatory frameworks designed to control industrial chemicals may not apply. It occurs at trace concentrations that challenge analytical detection and treatment removal. Its toxicity is highly species-specific, with some organisms affected at parts-per-trillion levels while others tolerate concentrations orders of magnitude higher. And its sources are diffuse and distributed—every road, every vehicle, every tire contributes to the problem.

3.2 The Remediation Gap

The challenge posed by 6PPD-quinone and similar emerging contaminants reveals a remediation gap: the mismatch between the scale and complexity of contamination problems and the capacity of available treatment technologies. Conventional water treatment processes—coagulation, sedimentation, filtration, disinfection—were designed primarily for pathogen removal and do not effectively remove trace organic contaminants. Advanced treatment options such as activated carbon adsorption, ozonation, and membrane filtration can achieve higher removal efficiencies but at significant cost and energy expenditure, making them impractical for treating the large volumes of stormwater that carry 6PPD-quinone to receiving waters.

Nanomaterials offer potential solutions to this gap, but their application to emerging contaminants has been limited. Nano-biochar and other adsorbents can capture 6PPD-quinone from aqueous solution, but the low concentrations and high flow rates characteristic of stormwater runoff create challenges for adsorption-based approaches. Photocatalytic degradation has shown promise in laboratory studies, but the transformation products of 6PPD-quinone degradation—and their toxicity—remain largely uncharacterized. The development of effective treatment technologies thus requires not only material innovation but also toxicological assessment, analytical method development, and systems-level design that addresses the full complexity of the problem.

Table 1 — Comparison of Remediation Technologies

Technology	Primary application	Main advantage	Key limitation
Nano-biochar	Heavy metals and emerging contaminants	High adsorption capacity and tunable surface properties	Potential nanoparticle release and uncertain environmental fate
Photocatalytic materials	Organic contaminant degradation and water treatment	Can degrade pollutants rather than concentrate them	Low efficiency, catalyst stability, and scale-up challenges
Conventional treatment	General water/stormwater treatment	Established infrastructure and operational experience	Limited effectiveness for some trace emerging contaminants

4. The Sustainability Question: Life-Cycle and Scalability Dimensions

4.1 Environmental Burdens of Production and Deployment

The environmental benefits of remediation technologies must be weighed against the environmental burdens of their production, use, and disposal. This life-cycle perspective reveals trade-offs that are often invisible when materials are evaluated solely on the basis of their technical performance.

The production of nano-biochar involves energy consumption for pyrolysis, mechanical energy for ball milling, and the use of chemical reagents for functionalization. While biochar production from waste biomass can be carbon-negative—storing carbon that would otherwise decompose to carbon dioxide—the additional processing required for nanoscale engineering may offset these gains. Life cycle assessment studies are needed to determine whether nano-biochar remediation achieves net environmental benefits when all stages of the life cycle are considered.

Photocatalytic systems present more complex trade-offs. The production of photocatalysts containing precious metals such as rhodium, palladium, and silver involves mining, refining, and manufacturing processes with significant environmental footprints. The amounts required may be small, but the environmental costs of extraction and processing can be substantial. Photocatalytic hydrogen production requires large land areas for solar collection, raising questions about land use competition that echo debates about renewable energy deployment more broadly (Buchadas et al., 2025).

The life cycle of remediation also includes the fate of spent materials. Adsorbents loaded with contaminants require regeneration or disposal, both of which generate environmental burdens. Photocatalysts degrade over time and must eventually be replaced. Recovery and recycling of valuable components—precious metals, for example—can reduce life-cycle burdens but requires infrastructure and energy that may not be available in all contexts.

4.2 Scalability and Deployment Challenges

Laboratory demonstrations of novel remediation materials often achieve impressive performance metrics that prove difficult to replicate at scale. The transition from bench-scale experiments to pilot-scale systems to full-scale deployment involves engineering, economic, and logistical challenges that are not captured in material characterizations alone.

The synthesis of functionalized nano-biochar requires specialized equipment—ball mills, pyrolysis reactors, chemical modification systems—that may not be available in regions where remediation is most needed. The cost of production, while potentially competitive with alternative adsorbents, may still be prohibitive for resource-constrained contexts. And the infrastructure for applying, recovering, and regenerating nano-biochar in field settings remains largely undeveloped.

Photocatalytic systems face similar scalability challenges. The scale-up of photocatalytic reactors requires optimization of light distribution, mass transfer, and catalyst recovery that differs fundamentally from laboratory configurations. The economics of photocatalytic hydrogen production depend on factors—solar irradiance, electricity prices, capital costs—that vary dramatically across locations, meaning that technologies viable in some contexts may be uneconomical in others (Huang et al., 2025).

The deployment of remediation technologies at scale also raises questions of governance and regulation. Nanomaterials are subject to evolving regulatory frameworks that may not adequately address their specific properties and risks. The lack of standard methods for characterizing nanomaterial toxicity and environmental fate creates uncertainty for developers and regulators alike. And the transboundary nature of many contaminant problems requires international coordination that is often difficult to achieve.

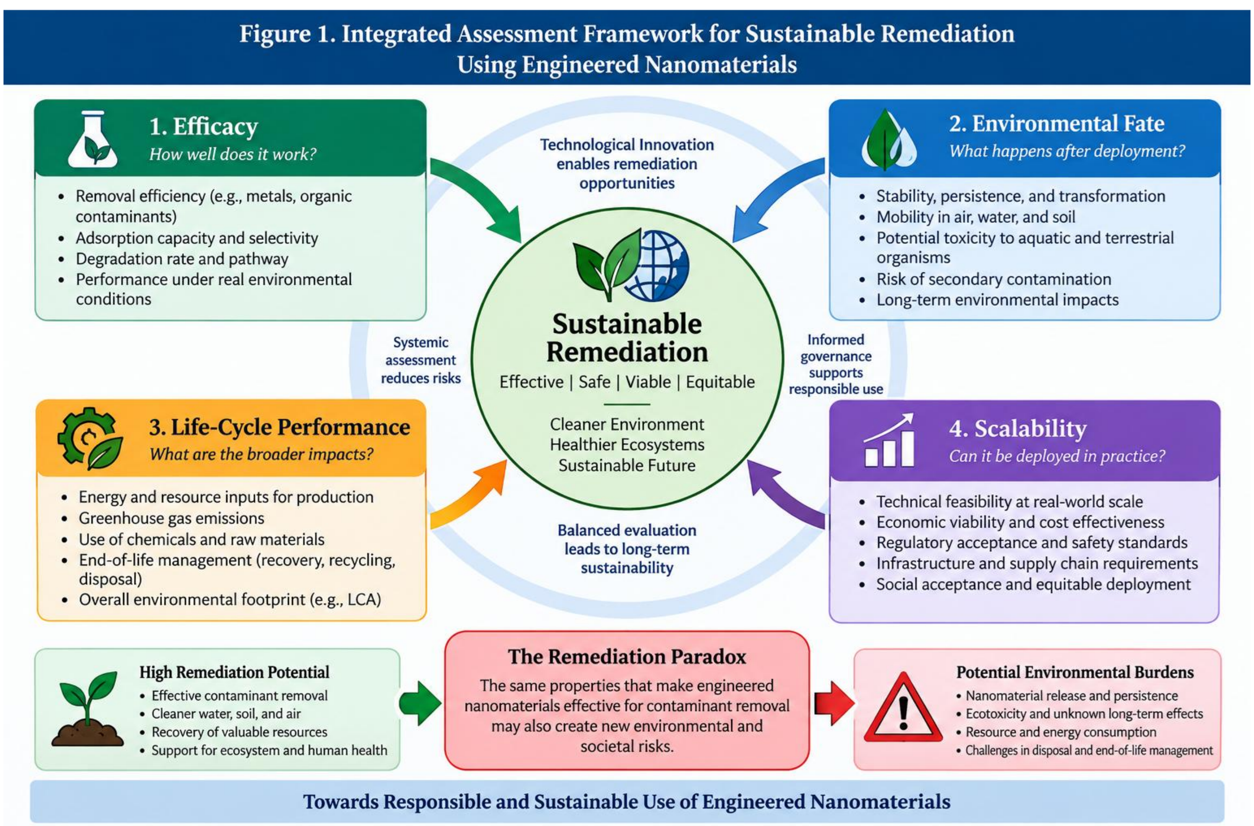
5. Toward Integrated Assessment and Sustainable Remediation

5.1 A Multi-Dimensional Assessment Framework

The complexity of remediation challenges—and the trade-offs inherent in any technological response—call for assessment frameworks that integrate multiple dimensions rather than optimizing along a single axis. Four dimensions are particularly critical: efficacy, environmental fate, life-cycle performance, and scalability.

Efficacy refers to the ability of a remediation technology to achieve its intended purpose—removing or degrading target contaminants to acceptable levels. This dimension is most familiar from laboratory studies and is typically characterized through metrics such as adsorption capacity, degradation rate, or removal efficiency. However, efficacy must be assessed across the full range of conditions likely to be encountered in application, including variations in contaminant concentration, competing ions, pH, temperature, and other water quality parameters.

Figure 1. Integrated assessment framework for sustainable remediation using engineered nanomaterials.



Environmental fate concerns the behavior of remediation materials themselves when released to the environment. For nanomaterials, this includes their persistence, mobility, transformation, and toxicity. The same properties that make nano-biochar an effective adsorbent—high surface area, reactivity—may also make it more mobile and potentially more toxic than bulk materials. Understanding the environmental fate of remediation materials is essential for ensuring that cleanup activities do not create new environmental problems.

Life-cycle performance encompasses the full range of environmental impacts associated with a technology from raw material extraction through production, use, and disposal. Life cycle assessment provides a systematic framework for quantifying these impacts, identifying hotspots, and comparing alternatives. However, applying life cycle assessment to nanomaterial-based remediation presents methodological challenges, including limited data on nanomaterial production and uncertainty about environmental fate and toxicity.

Scalability addresses the practical question of whether a technology can be deployed at the scale required to address real-world contamination problems. This includes technical scalability—whether performance can be maintained as systems grow—as well as economic scalability, regulatory scalability, and social scalability. Technologies that perform well in laboratory settings may prove impractical in field applications for reasons that have little to do with material properties.

Table 2 — Four-Dimensional Assessment Framework

Assessment dimension	Key question	Example indicators
Efficacy	How effectively does the technology remove or degrade contaminants?	Removal efficiency, adsorption capacity, degradation rate
Environmental fate	What happens to the remediation material after deployment?	Persistence, mobility, transformation, toxicity
Life-cycle performance	What are the environmental burdens throughout the technology life cycle?	Energy use, raw materials, production and disposal impacts
Scalability	Can the technology be practically deployed at real-world scale?	Technical, economic, regulatory and social feasibility

5.2 Case Analysis: Nano-Biochar for Heavy Metal Removal

Applying this framework to nano-biochar for heavy metal removal reveals both strengths and limitations. In terms of efficacy, nano-biochar demonstrates exceptional adsorption capacities that exceed those of conventional adsorbents and can be tailored through functionalization to target specific metals. However, performance under realistic conditions—with competing ions, natural organic matter, and variable pH—may differ from ideal laboratory conditions.

Environmental fate considerations include the potential for nanoparticle release to receiving waters, where their high surface area and reactivity could affect aquatic organisms and ecosystems. While biochar is generally considered benign compared to other nanomaterials, the effects of nanoscale biochar on aquatic life are not fully understood. The persistence of nano-biochar in the environment—estimated at decades to centuries—means that any adverse effects could be long-lasting.

Life-cycle assessment must account for the energy and materials required for pyrolysis, milling, and functionalization, as well as the environmental benefits of waste diversion and carbon sequestration. Whether nano-biochar remediation achieves net environmental benefit depends on system boundaries and allocation choices that remain contested.

Scalability questions include the availability of feedstock biomass, the capacity for distributed production, and the infrastructure for field application. While nano-biochar production could in principle be decentralized, the equipment and expertise required for quality control may limit deployment in resource-constrained settings.

5.3 Case Analysis: Photocatalytic Systems for Water Treatment and Hydrogen Production

Photocatalytic systems present a different profile across the assessment dimensions. Efficacy for water treatment is well-established for many organic pollutants, though complete mineralization is not always achieved and transformation products may retain toxicity. Co-production of hydrogen adds value but also complicates system design and operation.

Environmental fate concerns are less pronounced than for adsorbents, since photocatalysts are typically immobilized on supports rather than dispersed in treated water. However, catalyst degradation and leaching of components—particularly heavy metals—remains a concern.

Life-cycle performance is complicated by the use of precious metals and the energy requirements for system construction and operation. While photocatalytic systems derive their energy from sunlight, the embodied energy and materials in reactor construction and catalyst production may dominate life-cycle impacts.

Scalability is constrained by low solar-to-hydrogen efficiencies, high capital costs, and the need for large land areas. Integration with existing water treatment infrastructure could reduce costs and land requirements, but such integration remains largely unexplored.

6. Implications for Research and Policy

6.1 Research Priorities

Advancing sustainable remediation requires research that addresses the interconnections among efficacy, environmental fate, life-cycle performance, and scalability. Several priorities emerge from the analysis.

First, there is a need for integrated assessment tools that can evaluate remediation technologies across multiple dimensions simultaneously. Current approaches tend to focus on single dimensions—adsorption capacity, toxicity, cost—without systematically considering trade-offs. Developing multi-criteria assessment frameworks that incorporate environmental, economic, and social dimensions would support more informed decision-making.

Second, research on the environmental fate and effects of engineered nanomaterials must be expanded and accelerated. The rapid pace of material development has outpaced our understanding of how these materials behave in the environment. Predictive models, standardized testing protocols, and long-term monitoring studies are needed to assess the risks of nanomaterial release.

Third, life cycle assessment of remediation technologies should become standard practice rather than an afterthought. Understanding the full environmental footprint of a technology—from material extraction to end-of-life disposal—is essential for determining whether it represents a net environmental benefit. LCA studies should be conducted early in technology development to inform design decisions rather than merely documenting impacts after the fact.

Fourth, research on scaling and deployment must address not only technical challenges but also economic, regulatory, and social dimensions. Technologies that perform well in the laboratory may fail in the field for reasons that have little to do with material properties. Understanding the factors that enable or constrain deployment is essential for translating research advances into environmental benefit.

6.2 Policy Implications

The analysis has several implications for environmental policy. Regulatory frameworks for nanomaterials need to evolve to address the specific properties and risks of engineered materials. Current regulations, developed for bulk chemicals, may not adequately capture nanoscale-specific concerns. International coordination on nanomaterial regulation would help ensure consistent standards and avoid trade barriers.

Policies to promote sustainable remediation should incentivize life-cycle thinking. Subsidies, procurement requirements, and performance standards could all be designed to reward technologies that achieve environmental benefits without generating unacceptable burdens elsewhere in the life cycle.

Support for remediation research should prioritize integrated approaches that bridge materials science, environmental toxicology, life cycle assessment, and systems engineering. The challenges of sustainable remediation are inherently interdisciplinary, and progress will depend on researchers who can work across traditional boundaries.

Finally, policies should recognize that remediation is not a substitute for pollution prevention. The most sustainable approach to contamination is to prevent it in the first place. For emerging contaminants like 6PPD-quinone, where the source is diffuse and difficult to control, prevention may require fundamental changes in product design, manufacturing processes, and consumption patterns.

7. Conclusions

The development of engineered nanomaterials for environmental remediation represents a significant advance in the human capacity to address contamination problems. Nano-biochar, photocatalysts, and other advanced materials offer performance characteristics that exceed those of conventional approaches, enabling remediation of contaminants that were previously difficult or impossible to treat. Yet the same properties that make these materials effective also raise concerns about their environmental fate, life-cycle impacts, and scalability.

Resolving the remediation paradox requires moving beyond material-centric optimization to embrace systemic assessment. Efficacy, environmental fate, life-cycle performance, and scalability must be evaluated together rather than in isolation, with attention to trade-offs across environmental media, temporal scales, and stakeholder interests. Case analyses of nano-biochar for heavy metal removal and photocatalytic systems for water treatment and hydrogen production illustrate how this framework applies in practice, revealing both the potential and the limitations of current approaches.

The path toward sustainable remediation is not straightforward. It requires navigating tensions between efficacy and environmental safety, between local benefits and global burdens, between short-term needs and long-term consequences. These tensions cannot be resolved through technical means alone; they require ongoing deliberation among scientists, policymakers, industry, and affected communities about what sustainability means in specific contexts and how trade-offs should be weighed.

What is clear is that sustainable remediation cannot be achieved by optimizing individual technologies in isolation. It requires integrated approaches that consider the full life cycle of remediation materials, that assess environmental impacts across multiple dimensions, and that engage stakeholders in decisions about technology development and deployment. Only by adopting such approaches can we harness the potential of engineered nanomaterials while avoiding the creation of new environmental problems in the process.

References

Buchadas, A., Alves, A., Sequeira, M. M., Silva, R. A., Ferreira, V., & Lambin, E. F. (2025). A multiform energy transition: Typifying wind and solar energy-land systems in Portugal. *Manuscript submitted for publication*.

Dunlap, A., Sovacool, B. K., & Novaković, B. (2025). 'A dead sea of solar panels': Solar enclosure, extractivism and the progressive degradation of the California desert. *The Journal of Peasant Studies*, *52*(3), 539–573.

Gu, J., Liu, K., Yang, S., Sun, S., Liu, J., Li, X., Mu, H., Wen, Q., He, C.-S., & Lai, B. (2025). Tire-derived 6PPD-quinone in water: Environmental fate, ecological risks, and advances in its mitigation. *Environmental Science & Technology*, *59*(12), 6001–6015.

Huang, X., Jeswani, H. K., & Azapagic, A. (2025). Industrial-scale production of photocatalytic hydrogen in China: Life cycle environmental and economic assessment in comparison with other solar and conventional technologies. *Environmental Science & Technology*, *59*(8), 4102–4115.

Pathak, H. K., Seth, C. S., Chauhan, P. K., Dubey, G., Singh, G., Jain, D., Upadhyay, S. K., Dwivedi, P., & Khoo, K. S. (2024). Recent advancement of nano-biochar for the remediation of heavy metals and emerging contaminants: Mechanism, adsorption kinetic model, plant growth and development. *Environmental Research*, *255*, 119136.

Scott, D. N., & Smith, A. A. (2017). "Sacrifice zones" in the green energy economy: Toward an environmental justice framework. *McGill Law Journal*, *62*(3), 861–898.

Wang, D., Lin, J., Tang, J., Fu, Y., Liu, X., Wei, W., & Ni, B.-J. (2025). From naturally occurring to engineered nano-biochar: Properties, feasibility, and challenges for sustainable environmental remediation. *Environmental Science & Technology*, *59*(15), 7218–7235.