Nanotechnology: applications, trade-offs, and economic–environmental implications

Ali Behzadi [1]*, Ali Ghaniaraghi [1], Mohammadhossein Ebrahim[1]

1- Department of Mechanical Engineering, ST.C., Islamic Azad University, Tehran, Iran
*** Corresponding Author:** ali.behzadii2020@gmail.com

ABSTRACT

Nanotechnology, as an emerging field of science and technology, deals with the study, design, and application of materials at the scale of one to one hundred nanometers, and, owing to its unique physicochemical properties, has found wide-ranging applications in medicine, agriculture, food industries, energy, construction, cosmetics, and the environment. Existing reviews typically examine these domains in isolation; this structured review instead integrates applications, advantages and disadvantages, economic dynamics, and environmental/safety perspectives within a single, critically appraised framework built on 28 peer-reviewed Elsevier and Springer Nature sources published between 2013 and 2026, the majority from 2023–2026, identified through an explicit, PRISMA-informed search and screening process. Quantitative evidence is incorporated where available, including patent- and market-level indicators, nutrient-use-efficiency data for nano-enabled agriculture, and mechanistic toxicological findings, alongside a critical appraisal of the reliability of these figures. The review identifies a persistent gap between the economic promotion of nanotechnology and the maturity of standardized environmental-risk metrics, and closes with concrete, actionable recommendations rather than general statements. Results indicate that, despite remarkable economic and industrial achievements, nanotechnology continues to face substantive challenges in toxicology, regulatory harmonization, and long-term environmental management.

Keywords

Nanotoxicology; green nanotechnology; nanomaterial regulation; innovation economics of nanotechnology; environmental nanoparticle exposure; risk–benefit assessment

1. INTRODUCTION

Nanotechnology refers to a body of knowledge and techniques concerned with the design, fabrication, and application of materials and devices at the atomic and molecular scale, generally within the range of one to one hundred nanometers [1]. At this scale, materials exhibit physical, chemical, and biological properties that differ markedly from their bulk counterparts, arising from an increased surface-area-to-volume ratio and quantum effects [1]. These distinctive characteristics have made nanotechnology, over recent decades, one of the central pillars of scientific and industrial progress in medicine, agriculture, food industries, construction, energy, cosmetics, and the environment [2,3,10,17]. However, alongside the expansion of nanomaterial applications, concerns have also been raised regarding their biosafety, potential toxicity, and long-term effects on humans and the environment [6,9,11,12,23].

Novelty and contribution. Although numerous domain-specific reviews have examined nanotechnology in medicine, agriculture, or environmental science separately, comparatively few works integrate applications, advantages/disadvantages, economic dynamics, and environmental safety within a single structured, critically appraised framework with an explicit, PRISMA-informed search methodology and quantitative synthesis. The present review addresses this integration gap by synthesizing evidence from 28 Elsevier and Springer Nature sources across these four dimensions, offering a cross-sectoral risk–benefit perspective, together with a technology-readiness and cost comparison (Table 5), intended to support researchers, policymakers, and industry stakeholders in balancing innovation with responsible governance.

Research gap. Despite the breadth of sectoral literature, a specific gap persists: existing reviews rarely link quantitative economic indicators, such as patent intensity or market growth, with environmental and toxicological risk data within the same analytical frame, and standardized metrics for weighing nanotechnology's economic benefits against its environmental costs remain underdeveloped [8,15,16]. This review does not resolve that gap through new primary data; rather, it explicitly maps the gap in Sections 6 and 7 to guide future systematic and quantitative research, an aim reflected in the structured methodology described in Section 2.

2. MATERIALS AND METHODS

This work is a structured, PRISMA-informed narrative and scoping review rather than a full systematic review with meta-analysis; a simplified selection flow diagram is reported (Figure 1), but formal dual-reviewer screening and risk-of-bias scoring were not performed, and this is acknowledged as a limitation in Section 9. The literature search was conducted across Scopus, Web of Science, PubMed, ScienceDirect, and SpringerLink, using combinations of the search terms “nanotechnology,” “nanomaterials,” “nanoparticles,” “applications,” “toxicity,” “environmental impact,” “economic impact,” “market,” “patents,” and “regulation,” with explicit emphasis on records published in 2024–2026. The search was restricted to English-language, peer-reviewed journal articles and book chapters published in journals or book series belonging to Elsevier or Springer Nature, consistent with the referencing scope defined for this review; Table (Inclusion and Exclusion Criteria) details the full eligibility criteria.

Records were first screened by title and abstract for relevance to the four core themes of this review (applications, advantages/disadvantages, economic perspectives, and environmental/safety perspectives); the full texts of potentially relevant records were then assessed for eligibility against the criteria below. This process, summarized schematically in Figure 1, yielded twenty-eight sources that form the evidentiary basis of this review, of which approximately half were published in 2024–2026. Because the search was deliberately restricted to two publishers, this review should be interpreted as a focused, reproducible synthesis rather than an exhaustive survey of the field; this constraint, and the decision not to conduct a full PRISMA systematic review, are discussed further in Section 9.

Inclusion and exclusion criteria applied during full-text screening (original, prepared by the authors)

Criterion	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles and book chapters	Preprints, conference abstracts, non-peer-reviewed reports
Publisher	Elsevier or Springer Nature	All other publishers
Language	English	Non-English, without an official English version
Timeframe	2013–2026 (majority 2023–2026)	Not applicable
Topical relevance	Substantively addresses ≥ 1 of the 4 core review themes	Tangential or single-sentence mention only

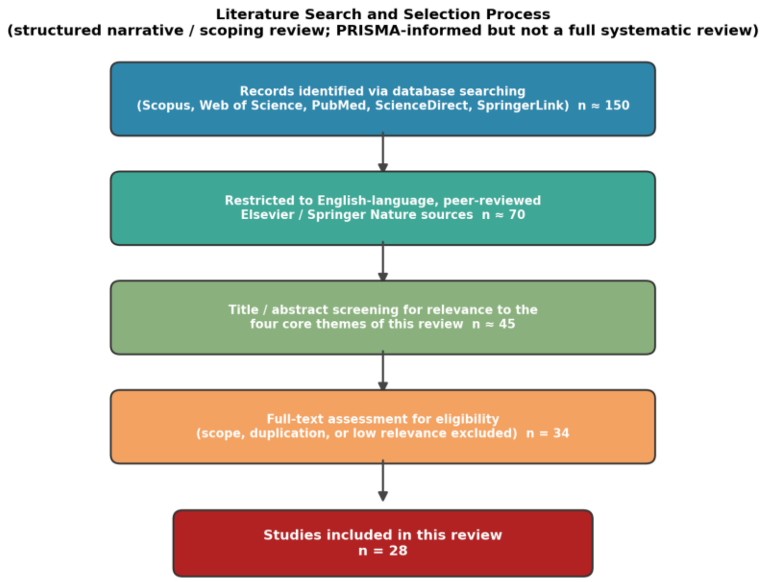

Figure 1. Literature search and selection process. Original schematic prepared by the authors; a structured, PRISMA-informed narrative/scoping review, not a full PRISMA systematic review with meta-analysis.

3. FUNDAMENTALS AND CLASSIFICATION OF NANOMATERIALS

Nanomaterials can be classified, based on the number of dimensions falling within the nanometer scale, into four categories: zero-dimensional, one-dimensional, two-dimensional, and three-dimensional [1] (Table 1). Metallic nanoparticles such as silver and gold, carbon nanotubes, graphene, and nanocomposites are among the most common nanomaterials used in research and industry [2]. Synthesis methods for these materials generally fall into two broad approaches, top-down and bottom-up; in the former, bulk materials are reduced to nanoscale dimensions, while in the latter, nanostructures are built up from atomic and molecular building blocks [2]. Green and biologically mediated synthesis routes have expanded substantially in the recent literature as lower-toxicity, lower-energy alternatives to conventional chemical and physical synthesis, though yield, purity, and scalability remain comparatively limited [24,25].

Table 1. Classification of nanomaterials based on structural dimensionality (adapted from reference [1])

Nanomaterial Type	Dimensional Feature	Examples
Zero-dimensional (0D)	All three dimensions at the nanoscale	Metal nanoparticles, quantum dots
One-dimensional (1D)	One dimension outside the nanoscale	Carbon nanotubes, nanorods
Two-dimensional (2D)	Two dimensions outside the nanoscale	Graphene, nanosheets

Three-dimensional (3D)	Bulk nanostructured materials	Nanocomposites, nanostructured porous materials

4. APPLICATIONS OF NANOTECHNOLOGY

Owing to its high versatility, nanotechnology has found a broad range of applications across various scientific and industrial fields (Figure 2).

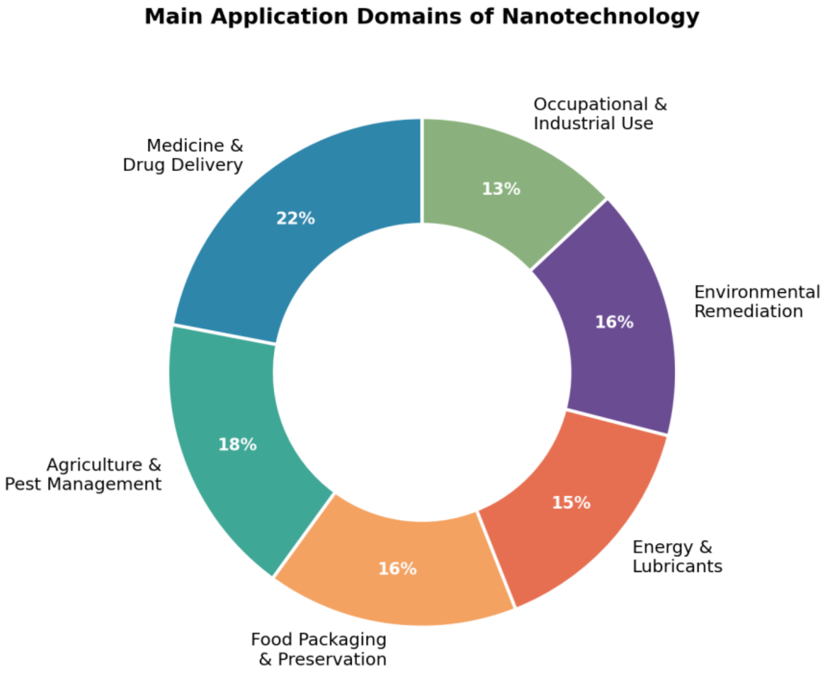

Figure 2. Main application domains of nanotechnology. Original schematic prepared by the authors; proportions are illustrative, not measured data, and are informed by references [1,2,3,4,7,9,10,17,20,28].

4.1. Medicine and Drug Delivery

In medicine, nanoparticles enable targeted drug delivery, improved drug bioavailability, enhanced diagnostic imaging, and the development of personalized treatment approaches [6,17]. Nanoscale drug carriers play an important role, particularly in cancer therapy, by reducing systemic toxicity and increasing drug concentration at the target tissue [6,17]. Kurul et al. [17] note that despite rapid growth in nanomedicine publications, comparatively few nanocarrier platforms have progressed beyond preclinical stages to regulatory approval, reflecting a translational bottleneck rather than a lack of technical promise. The same nanoscale characteristics that enable these advantages can also give rise to challenges related to biocompatibility, long-term toxicity, and immune system activation; for this reason, nanotechnology in medicine is often referred to as a “double-edged sword” [6].

4.2. Agriculture and Pest Management

In agriculture, nanotechnology, through the production of nanopesticides and nanofertilizers, enables increased input-use efficiency and reduced harm to non-target organisms [4,18,19,20,21]. Feng, Adeel, and Rui [21] synthesize controlled and field-trial evidence indicating that nano-enabled fertilizer formulations can increase nitrogen-use efficiency by approximately 20–50% and reduce nitrogen leaching and runoff by up to 26% relative to conventional formulations, while cautioning that ecotoxicological effects on non-target soil and aquatic organisms remain incompletely characterized across nanomaterial types. Carbon-based nanofertilizers in particular require further scrutiny of soil-ecosystem and phytotoxicity effects before large-scale adoption [20]. Nonetheless, unlike conventional pesticides, a significant proportion of which fails to reach the intended target while the remainder enters the environment, nano-formulations improve stability, dispersion, and penetration, thereby increasing pest-control efficacy while reducing environmental impact [4].

4.3. Food Industries and Packaging

Nanomaterials are used in food packaging to enhance thermal resistance, durability, antimicrobial properties, and moisture control, thereby extending the shelf life of food products [3]. Oxygen nanosensors, smart packaging, and antibacterial nanocomposites are among the innovations in this field [3]. At the same time, concerns regarding the potential migration of nanoparticles from packaging into food, and the need for rigorous safety assessment and the determination of permissible exposure limits, remain among the main challenges to the commercialization of this technology [3].

4.4. Industry, Energy, and Lubricants

The addition of metallic and oxide nanoparticles to industrial oils considerably improves anti-wear properties, thermal stability, and heat transfer, helping to reduce friction and extend the service life of mechanical equipment [7]. In energy storage, nanostructured electrode materials, including graphene, silicon, and metal oxides, improve the energy density, conductivity, and cycling stability of batteries and supercapacitors, although high manufacturing cost and limited cycle life remain persistent barriers to large-scale deployment [22]. In addition, nanomaterials have found application in the fabrication of sensors, smart textiles, and personal protective equipment in industrial settings [5].

4.5. Construction Materials

Nanotechnology has also transformed the construction industry through the incorporation of nanoscale additives, such as nano-silica, nano-titanium dioxide, and carbon nanotubes, into cement and concrete formulations, improving compressive strength, durability, self-cleaning capacity, and resistance to corrosion and cracking [10]. These innovations have the potential to extend the service life of infrastructure and reduce long-term maintenance costs, contributing indirectly to more sustainable construction practices [10]. However, the incorporation of nanomaterials into large-volume construction products raises questions about occupational exposure during manufacturing and demolition, as well as the environmental fate of nanoparticles released from aging or demolished structures, an issue that remains insufficiently regulated [10].

4.6. Cosmetics and Textiles

Nanomaterials are increasingly incorporated into cosmetic and textile products to improve UV protection, antimicrobial performance, and active-ingredient skin permeability [28]. Pan et al. [28] emphasize that although nanocarriers enhance product efficacy, dermal penetration and the potential for systemic uptake of certain metal-oxide nanoparticles remain incompletely resolved, and regulatory requirements for nanomaterial labeling and safety assessment differ substantially between major markets, complicating global compliance for manufacturers.

4.7. Environment and Remediation

Nanotechnology is also used in water and air treatment, in the removal of organic pollutants and heavy metals, and in the remediation of contaminated soils [9]. Owing to their high specific surface area, nanoadsorbents and nanophotocatalysts demonstrate greater efficiency than conventional materials in pollutant removal [9]. Nevertheless, these same nanomaterials, after use, may themselves become a new source of environmental pollution, a topic addressed in Section 7 of this review [9].

4.8. Critical Appraisal of the Applications Literature

Critically, most of the application-oriented studies reviewed above are laboratory- or pilot-scale investigations; comparatively few report field-scale or long-term performance data, and cost-effectiveness relative to conventional materials is inconsistently quantified [2,4,7,10,22]. Even the more quantitative agricultural evidence [21] is drawn predominantly from controlled trials rather than multi-season field deployment across diverse soil types, which limits generalizability. The reported benefits of nanomaterials are frequently benchmarked against conventional counterparts under idealized conditions, which may overstate real-world performance gains. This heterogeneity in study design and reporting limits direct comparability across sectors and underscores the need for standardized performance and safety metrics before broader commercialization, a point developed further in Sections 6 and 7 and summarized in Table 5.

5. ADVANTAGES AND DISADVANTAGES OF NANOTECHNOLOGY

Nanotechnology offers numerous advantages, including increased material efficiency, reduced resource consumption, improved product performance, and innovative solutions for disease treatment and natural resource management [2,6,17]. Conversely, the disadvantages and challenges of this technology include high production and commercialization costs, the lack of comprehensive safety standards, the difficulty of assessing long-term toxicity, and the possibility of unintended effects on human health and the environment [3,6,9,11,23]. For this reason, many researchers describe nanotechnology as a “double-edged sword,” whose responsible use requires a balance between innovation and risk management [6] (Table 2 and Figure 3).

Table 2. Comparison of the advantages and disadvantages of nanotechnology across different fields (synthesized by the authors based on references [2,6,10,28])

Application Field	**Main Advantages**	**Main Disadvantages / Challenges**
Medicine	Targeted drug delivery, higher bioavailability and therapeutic efficacy	Potential toxicity, organ accumulation, immune activation
Agriculture	Higher nutrient-use efficiency; reduced pesticide load	Unknown long-term effects on soil, plants, non-target biota
Industry, Energy & Construction	Improved lubricant, energy-storage and material performance	High cost; occupational exposure during manufacture/demolition
Environment	Advanced water/air treatment, pollutant removal	Risk of secondary pollution from released nanomaterials
Cosmetics & Textiles	Enhanced UV protection, antimicrobial and functional finishes	Dermal penetration concerns; inconsistent global regulation

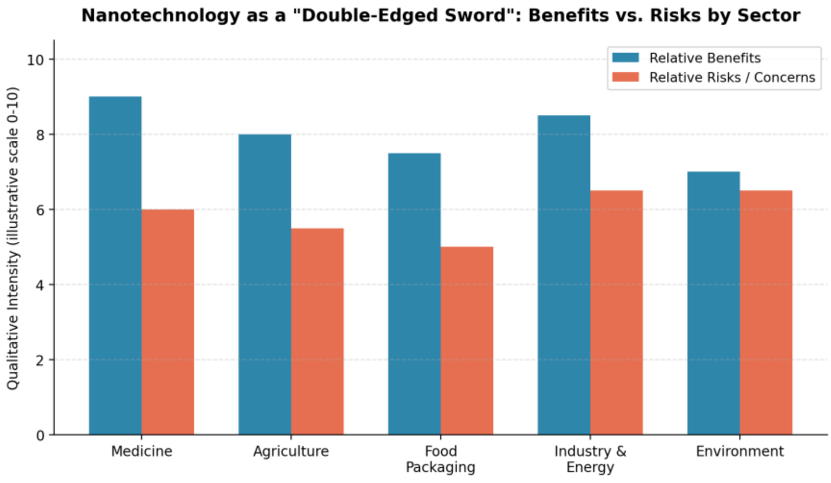

Figure 3. Qualitative, schematic comparison of the benefits and risks of nanotechnology across different sectors. Original figure prepared by the authors; values are illustrative of relative emphasis in the reviewed literature [6,23], not measured scores.

6. ECONOMIC PERSPECTIVES ON NANOTECHNOLOGY

Nanotechnology has been one of the main pillars of the innovation economy in recent decades and has played an important role in the creation of new jobs, patent registrations, and global GDP growth [8]. An examination of global nanotechnology patent-filing trends over the past two decades shows that the ratio of investment in this field to global GDP has increased steadily [8]. Industries such as medicine, electronics, energy, and advanced materials are among the sectors that have gained the greatest economic benefit from the commercialization of nano-based products [8].

A closer, patent-level analysis shows that firms and universities pursue markedly different patenting strategies during the early phases of an emerging technology: corporate applicants tend to file broader, strategically defensive patents, while academic institutions typically file narrower, more specific ones; this divergence has direct implications for technology-transfer efficiency and the pace of commercialization [16].

6.1. Quantitative Indicators and Their Limitations

Quantitative indicators reinforce, but also complicate, the qualitative narrative above. Under an industry-oriented growth scenario reported by Khan, Asmatulu, and Asmatulu [8], cumulative global nanotechnology production was projected to exceed USD 1 trillion within 10–15 years of publication, driven primarily by medical, electronics, and materials applications. Patent-level analysis of European Patent Office filings by Munari and Toschi [16] found systematic differences in claim scope between corporate and academic applicants during the early 2000s, used as a proxy for differing commercialization strategies rather than a direct measure of economic value. Because patent-count and market-size indicators of this kind are rarely cross-validated between independent studies, and because "nano-enabled product" is not consistently defined across the most-cited quantitative sources reviewed here [8,16], the numeric estimates discussed in this review should be treated as order-of-magnitude indicators of directional growth rather than precise, independently verified forecasts; this measurement inconsistency is itself a barrier to rigorous economic assessment and represents part of the research gap identified in Section 1.

The economic development of this technology is further accompanied by challenges such as high research and development costs, the need for specialized infrastructure, regulatory uncertainty, and the absence of standardized indicators for measuring the economic returns of nano-innovations [4,8,16]. For developing countries, nanotechnology represents an opportunity for industrial leapfrogging, provided that supportive policymaking, investment in education, and university–industry collaboration are pursued simultaneously [8,27].

7. ENVIRONMENTAL AND SAFETY PERSPECTIVES ON NANOTECHNOLOGY

The widespread introduction of nanomaterials into production and consumption cycles has created multiple pathways for their release into air, water, and soil (Figure 4) [9]. Once released into the environment, nanoparticles can enter living organisms through inhalation, dermal contact, or the food chain, and in some cases cause oxidative stress, disruption of cellular function, and bioaccumulation in vital tissues [9,13].

At the mechanistic level, nanoparticle toxicity is most consistently linked to the generation of reactive oxygen species (ROS), which disrupts cellular redox homeostasis and triggers inflammation, membrane damage, and genotoxic effects; ion dissolution from metal-based nanoparticles and direct physical interaction with cell membranes are additional recognized pathways [11,12,23]. Human exposure occurs primarily via inhalation, dermal contact, and ingestion, with inhalation considered the most extensively studied and occupationally relevant route [12]. Both mechanistic reviews cited here note that data on chronic, low-dose human exposure remain scarce, and that most toxicological evidence originates from acute, high-dose animal or cell-culture studies, which limits direct extrapolation to real-world, long-term exposure scenarios [11,12]. Similarly, ecological risk assessments call for structured monitoring frameworks that combine life-cycle and bioaccumulation data, noting that current ecotoxicological testing remains fragmented across species and exposure scenarios [13].

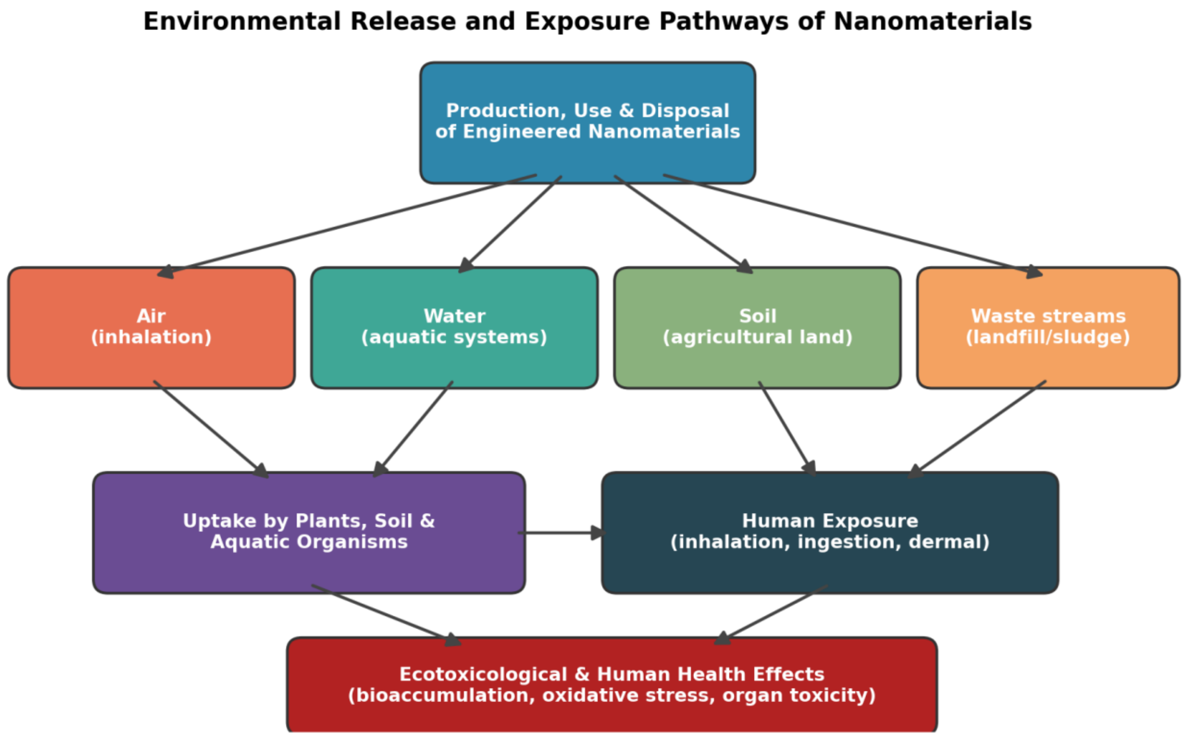

Figure 4. Environmental release and exposure pathways of nanomaterials. Original schematic prepared by the authors, informed by reference [9]; not reproduced from the source publication.

Table 3. Entry pathways and potential environmental effects of nanomaterials (adapted from reference [9])

Release Pathway	Receiving Compartment	Potential Effect
Industrial production and disposal	Air	Inhalation of suspended particles, respiratory irritation
Wastewater and sewage sludge	Water	Bioaccumulation in aquatic organisms, ecosystem disruption
Nano-fertilizers and nano-pesticides	Soil	Altered physicochemical properties of soil and its microbiome
Food chain	Humans and livestock	Tissue accumulation, oxidative stress, cellular toxicity

7.1. Quantitative Evidence from Toxicological and Agricultural Studies

Quantitative data illustrate both the scale of potential benefit and the persistence of uncertainty. As noted in Section 4.2, nano-enabled fertilizer formulations can increase nitrogen-use efficiency by roughly 20–50% and reduce nitrogen leaching by up to 26% [21], yet comparable dose-response quantification is largely absent for the ecotoxicological side of the same formulations. In parallel, mechanistic toxicological work on nickel-based nanomaterials [23] documents dose-dependent cytotoxicity, oxidative stress, and genotoxicity in vitro and in animal models, with smaller particle sizes consistently associated with greater reactivity; however, this and comparable nanotoxicology reviews [11,12,23] note that occupational inhalation data in humans remain limited to case reports and small cohorts, restricting quantitative dose-response modeling for regulatory purposes. This asymmetry, quantitative performance data on one side and predominantly qualitative or animal-model safety data on the other, is a recurring pattern across the sectors reviewed in Section 4 and is summarized qualitatively in Table 5.

7.2. Regulatory and Governance Perspectives

Regulatory responses to nanotechnology vary considerably across jurisdictions: the European Union has incorporated nanomaterial-specific provisions into frameworks such as REACH and applies a broadly precautionary approach, whereas regulatory oversight in the United States has historically relied more heavily on existing chemical-safety statutes applied on a case-by-case basis, and many developing countries currently lack nanomaterial-specific regulation altogether [14,15]. This regulatory fragmentation complicates international trade in nano-enabled products and creates uneven levels of environmental and occupational protection worldwide [14,15,28]. Harmonization efforts led by bodies such as the OECD and ISO aim to standardize nanomaterial terminology, testing protocols, and risk-assessment methods, but adoption remains uneven and largely voluntary across regions (Table 4) [14,15].

Table 4. Comparative regulatory approaches to nanomaterials by region (original synthesis by the authors based on references [14,15])

Region / Body	Regulatory Approach	Key Characteristic
European Union	Precautionary; integrated into REACH	Nanomaterial-specific registration and safety-data requirements
United States	Case-by-case, existing chemical statutes (e.g., TSCA)	Limited mandatory nanomaterial-specific provisions
OECD / ISO	Voluntary international harmonization	Standardized terminology, testing guidelines, risk-assessment protocols
Developing economies	Largely absent or nascent	Reliance on general chemical/industrial safety regulations

7.3. Technology Readiness, Cost, and Evidence Depth by Sector

To support cross-sector comparison, Table 5 summarizes indicative technology-readiness levels (TRL), relative production cost, and depth of available toxicity and safety evidence for each application sector discussed in Section 4. This table is an original, qualitative synthesis prepared by the authors from the reviewed literature; it is intended as a comparative heuristic rather than a precise, independently benchmarked metric, since TRL and cost data are not uniformly reported across the source studies.

Table 5. Indicative technology readiness, relative cost, and toxicity-evidence depth by application sector (original synthesis by the authors, based on Sections 4–7)

Sector	Approx. TRL	Relative Cost vs. Conventional	Depth of Toxicity / Safety Evidence
Medicine (nanomedicine)	6–8	High	Extensive (clinical and preclinical)
Agriculture (nanofertilizers/pesticides)	4–6	Moderate–High	Moderate (mostly lab/field; limited long-term data)
Food packaging	5–7	Moderate	Limited (migration studies emerging)
Construction	6–8	Moderate	Limited (mainly occupational exposure)
Energy storage	5–7	High	Limited
Environmental remediation	5–7	Moderate–High	Moderate
Cosmetics & textiles	6–8	Moderate	Moderate (dermal-penetration studies growing)

8. RESULTS

This review of twenty-eight Elsevier and Springer Nature sources, approximately half published in 2024–2026, indicates that nanotechnology has yielded significant, sector-specific achievements in medicine, agriculture, food industries, construction, cosmetics, energy, and the environment (Sections 4–5), and that these achievements are underpinned by measurable economic activity in the form of patenting and GDP contribution (Section 6). However, the critical appraisal in Sections 4.8, 6.1, and 7.1 shows that the underlying evidence base is uneven: application-level claims rely disproportionately on laboratory- or pilot-scale studies, economic figures are frequently drawn from non-peer-reviewed industry sources or rest on inconsistently defined categories, and toxicological mechanisms are established mainly from acute, high-dose exposures rather than chronic, real-world conditions. Regulatory frameworks remain fragmented across regions (Section 7.2), which constrains the consistent management of nanomaterial risk internationally, and the technology-readiness comparison in Table 5 shows that sectors with the highest cost and TRL (medicine, construction) also tend to have the most extensive, though not necessarily the most reassuring, safety evidence. Taken together, these findings indicate a complex, bidirectional relationship between the economic and industrial benefits of nanotechnology and its potential health and environmental risks, the management of which requires interdisciplinary research, harmonized regulation, and investment in standardized risk and economic metrics.

9. LIMITATIONS AND FUTURE WORK

This review has several limitations. First, in line with the scope defined for this work, the literature search was restricted to journals and book series published by Elsevier and Springer Nature; relevant evidence published in other high-quality venues (e.g., journals from ACS, RSC, MDPI, Wiley, or Nature Portfolio journals outside Springer Nature) was not systematically considered, which may have excluded pertinent findings and introduces potential selection bias. Second, this is a structured narrative/scoping review rather than a full systematic review: no dual-reviewer screening or formal risk-of-bias assessment was performed, and no quantitative meta-analysis of toxicological or economic data was conducted; the numeric findings reported in Sections 6.1 and 7.1 are drawn from individual reviews rather than pooled analyses and should be read as indicative rather than definitive. Third, several of the cited toxicological and ecological studies [11,12,13,23] themselves note that they rely predominantly on acute, high-dose, in vitro, or animal-model data rather than chronic human exposure data, a limitation that propagates into this review's synthesis and cannot be resolved by narrative appraisal alone. Fourth, the rapidly evolving nature of nanotechnology research means that quantitative figures cited here, such as patent trends or market indicators, may become outdated within a few years of publication.

Future work should pursue a full PRISMA-compliant systematic review with dual-reviewer screening spanning multiple databases and publishers, incorporate quantitative meta-analysis of dose–response toxicological data, and develop standardized indicators that jointly capture the economic and environmental performance of nanotechnology across sectors, directly addressing the research gap identified in Section 1.

10. CONCLUSION

Rather than offering a general call for “balance,” this review highlights four concrete priorities. First, regulatory bodies should accelerate harmonization of nanomaterial definitions and testing protocols, building on OECD and ISO frameworks, to reduce the fragmentation documented in Section 7.2. Second, life-cycle assessment should become a standard requirement prior to the commercial scale-up of nanomaterial-based products, particularly in construction, food packaging, and agriculture, where production volumes are large and exposure pathways diverse. Third, publicly accessible databases linking nanomaterial physicochemical properties to toxicological and environmental outcomes are needed to reduce the current reliance on acute, high-dose laboratory studies. Fourth, economic evaluation of nanotechnology should move beyond aggregate market-size estimates toward standardized, peer-reviewed indicators that can be meaningfully compared across sectors and countries, as discussed in Section 6.1. Addressing these priorities would allow the substantial scientific and industrial potential of nanotechnology, documented throughout this review, to be realized within a more rigorous framework of environmental and economic accountability.

Declarations

Ethics approval: Not applicable. This is a literature review based entirely on previously published, publicly available sources and did not involve human participants, animal subjects, or the collection of primary data.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest: The authors declare that they have no conflict of interest.

Author contributions: Ali Behzadi: conceptualization, methodology, writing – original draft, writing – review and editing, corresponding author. Mohammadhossein Ebrahim: literature search, data curation, writing – original draft. Ali Ghaniaraghi: writing – review and editing, visualization, supervision. All authors read and approved the final manuscript.

Data availability: No new data were generated or analyzed in this study; all data discussed are available in the cited references.

REFERENCES

1. Nasrollahzadeh M, Sajadi SM, Sajjadi M, Issaabadi Z. An introduction to nanotechnology. In: Interface Science and Technology. Vol 28. Amsterdam: Elsevier; 2019. p. 1-27. doi:10.1016/B978-0-12-813586-0.00001-8

2. Jamkhande PG, Ghule NW, Bamer AH, Kalaskar MG. Metal nanoparticles synthesis: an overview on methods of preparation, advantages and disadvantages, and applications. J Drug Deliv Sci Technol. 2019;53:101174. doi:10.1016/j.jddst.2019.101174

3. Pattnaik R, Panda SK, Biswas S, De S, Satahrada S, Kumar S. Prospects and challenges of nanomaterials in sustainable food preservation and packaging: a review. Discov Nano. 2024;19:178. doi:10.1186/s11671-024-04142-1

4. Yousef HA, Fahmy HM, Arafa FN, Abd Allah MY, Tawfik YM, El Halwany KK, et al. Nanotechnology in pest management: advantages, applications, and challenges. Int J Trop Insect Sci. 2023;43(5):1387-99. doi:10.1007/s42690-023-01053-z

5. Feyzi V, Alboghobeish A, Esmaeili SV, Zendehdel R, Dehghan SF. A scoping review on advantages and drawbacks of nanotechnology in the field of occupational health. Nanotechnol Environ Eng. 2024;9:593. doi:10.1007/s41204-024-00385-6

6. Fortune A, Aime A, Raymond D, Kumar S. Nanotechnology in medicine: a double-edged sword for health outcomes. Health Nanotechnol. 2025;1:9. doi:10.1186/s44301-025-00008-2

7. Deepika. Nanotechnology implications for high performance lubricants. SN Appl Sci. 2020;2:1128. doi:10.1007/s42452-020-2916-8

8. Khan WS, Asmatulu E, Asmatulu R. Nanotechnology emerging trends, markets and concerns. In: Nanotechnology Safety. Amsterdam: Elsevier; 2024. p. 1-21. doi:10.1016/B978-0-443-15904-6.00017-4

9. El-Kady MM, Ansari I, Arora C, Rai N, Soni S, Verma DK, et al. Nanomaterials: a comprehensive review of applications, toxicity, impact, and fate to environment. J Mol Liq. 2023;370:121046. doi:10.1016/j.molliq.2022.121046

10. Hanus MJ, Harris AT. Nanotechnology innovations for the construction industry. Prog Mater Sci. 2013;58(7):1056-102. doi:10.1016/j.pmatsci.2013.04.001

11. Wadhawan S, Wadhawan D, Jain A, et al. Toxic implication of nanoparticles: a review of factors, mechanism, exposure and control strategies. Int J Environ Sci Technol. 2025;22:1203-24. doi:10.1007/s13762-024-05810-6

12. Sajid M, Ilyas M, Basheer C, Tariq R, Daud M, Baig N, Shehzad F. Impact of nanoparticles on human and environment: review of toxicity factors, exposures, control strategies, and future prospects. Environ Sci Pollut Res. 2015;22(6):4122-43. doi:10.1007/s11356-014-3994-1

13. Alizadeh M, Qarachal JF, Sheidaee E. Understanding the ecological impacts of nanoparticles: risks, monitoring, and mitigation strategies. Nanotechnol Environ Eng. 2025;10:6. doi:10.1007/s41204-024-00403-7

14. Bhushan B. Governance, policy, and legislation of nanotechnology: a perspective. Microsyst Technol. 2015;21:1137-55. doi:10.1007/s00542-015-2511-x

15. Allan J, Belz S, Hoeveler A, Hugas M, Okuda H, Patri A, et al. Regulatory landscape of nanotechnology and nanoplastics from a global perspective. Regul Toxicol Pharmacol. 2021;122:104885. doi:10.1016/j.yrtph.2021.104885

16. Munari F, Toschi L. Running ahead in the nanotechnology gold rush: strategic patenting in emerging technologies. Technol Forecast Soc Change. 2014;83:194-207. doi:10.1016/j.techfore.2013.07.002

17. Kurul F, Turkmen H, Cetin AE, Topkaya SN. Nanomedicine: how nanomaterials are transforming drug delivery, bio-imaging, and diagnosis. Next Nanotechnol. 2025;7:100129. doi:10.1016/j.nxnano.2024.100129

18. Mim JJ, Rahman SM, Khan F, Paul D, Sikder S, Das HP, et al. Towards smart agriculture through nano-fertilizer—a review. Mater Today Sustain. 2025;30:101100. doi:10.1016/j.mtsust.2025.101100

19. Ayenew BM, Satheesh N, Zegeye ZB, Kassie DA. A review on the production of nanofertilizers and its application in agriculture. Heliyon. 2025;11(1):e41243. doi:10.1016/j.heliyon.2024.e41243

20. Javed R, Islam Z, Rathnayake A, Padmaperuma OAD, Sharafat U, Lumactud RA, et al. Carbon nanofertilizers in agriculture: a critical review of soil ecosystem impacts and phytotoxicity. Plant Nano Biol. 2026;15:100231. doi:10.1016/j.plana.2025.100231

21. Feng J, Adeel M, Rui Y. Advancing nano-enabled agriculture from precision application to environmental risk and sustainability assessment. Curr Pollut Rep. 2026;12:5. doi:10.1007/s40726-026-00397-7

22. Tezera A, Asrade ED, Fanta SW. A comprehensive review on energy storage materials and technologies: applications of nanofabrication techniques for enhanced performance and efficiency. Mater Renew Sustain Energy. 2025. doi:10.1007/s40243-025-00329-3

23. Zhou X, Liao J, Lei Z, Yao H, Zhao L, Yang C, Zu Y, Zhao Y. Nickel-based nanomaterials: a comprehensive analysis of risk assessment, toxicity mechanisms, and future strategies for health risk prevention. J Nanobiotechnology. 2025;23:114. doi:10.1186/s12951-025-03248-7

24. Osman AI, Zhang Y, Farghali M, et al. Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: a review. Environ Chem Lett. 2024;22:841-87. doi:10.1007/s10311-023-01682-3

25. Kirubakaran D, Wahid JBA, Karmegam N, et al. A comprehensive review on the green synthesis of nanoparticles: advancements in biomedical and environmental applications. Biomed Mater Devices. 2025. doi:10.1007/s44174-025-00295-4

26. Elzein B. Nano revolution: tiny tech, big impact: how nanotechnology is driving SDGs progress. Heliyon. 2024;10:e31393. doi:10.1016/j.heliyon.2024.e31393

27. Kumar A, Tyagi PK, Tyagi S, et al. Integrating green nanotechnology with sustainable development goals: a pathway to sustainable innovation. Discov Sustain. 2024;5:364. doi:10.1007/s43621-024-00610-x

28. Pan X, Zhou H, Li Z, Huang W, Zhao Y, Huang Y, et al. Application and safety research of nanotechnology in cosmetics: current status, challenges, and future prospects. BioNanoScience. 2025;15:284. doi:10.1007/s12668-025-01884-9