Understanding the Toxicological Effects of Nanomaterials on Human Health and the Environment: A Systematic Review

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ABSTRACT

Background

Nanomaterials (NMs) are increasingly utilized across industrial, biomedical, and consumer sectors, raising concerns about potential human and environmental toxicity.

Objectives

This systematic review synthesizes epidemiological, occupational, and mechanistic evidence on the toxicological effects of engineered nanomaterials (ENMs), emphasizing oxidative stress and biological perturbations in humans and ecological systems.

Methods

Peer-reviewed studies (2007–2025) were analyzed, including cross-sectional, longitudinal, and in vitro investigations on metal oxide and carbon-based NMs. Quantitative exposure levels, biological markers, and mechanistic outcomes were extracted and compared.

Results

Across ten core studies, oxidative stress emerged as a consistent mechanistic pathway. Occupational cohorts showed mild pulmonary and cardiovascular changes, while in vitro models revealed reactive oxygen species–mediated apoptosis and enzyme inhibition. Dermal toxicity resulting from ion release and chronic subclinical effects associated with carbon nanomaterials were also observed.

Conclusions

The integrated findings support oxidative stress, inflammation, and subclinical pulmonary effects as early indicators of nanotoxicity. Although overt disease remains rare, the biological evidence underscores the need for biomonitoring, exposure reduction, and harmonized global surveillance to mitigate chronic risk.

Keywords: Nanotoxicology; Oxidative stress; Engineered nanomaterials; Occupational exposure; Metal oxide nanoparticles; Carbon nanotubes; Environmental health; Biomonitoring

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Introduction

Nanotechnology has revolutionized numerous sectors—ranging from medicine and electronics to energy and environmental engineering—by enabling the manipulation of matter at the nanoscale. However, the unique physicochemical properties that make nanomaterials (NMs) so valuable also present potential risks to human health and ecological systems. Their high surface area-to-volume ratio, reactivity, and capacity to cross biological barriers can enhance bioavailability and toxicity compared to their bulk counterparts (Kumah et al., 2023). Consequently, understanding how these materials interact with biological systems has become a critical component of modern toxicological research and risk assessment.

The widespread integration of engineered nanomaterials (ENMs) in industrial production, pharmaceuticals, and consumer products has raised increasing concern about chronic and occupational exposure. Evidence suggests that even low-level, long-term exposure to ENMs may lead to oxidative stress, inflammation, and genotoxicity, particularly when inhaled or absorbed through the skin (Halamoda-Kenzaoui et al., 2022). The complexity of these interactions necessitates comprehensive evaluations, combining *in vitro*, *in vivo*, and human epidemiological approaches to determine safe

exposure thresholds and identify susceptible populations.

The toxic potential of nanomaterials depends heavily on multiple intrinsic and extrinsic factors, including particle size, morphology, solubility, surface charge, and aggregation behavior in biological or environmental media. Nanoparticles smaller than 100 nm can penetrate cell membranes, translocate to systemic circulation, and accumulate in organs such as the lungs, liver, kidneys, and brain (Pietroiusti et al., 2018). Once internalized, they may disrupt cellular homeostasis through oxidative stress or by interfering with mitochondrial and lysosomal functions.

In occupational settings, inhalation remains the primary exposure route for nanomaterials. Epidemiological studies among nanotechnology workers have reported early biomarkers of pulmonary inflammation, mild declines in lung function, and alterations in oxidative stress enzymes, although definitive causal links are still being established (Schulte et al., 2019). Despite technological advances in exposure assessment and control, the lack of harmonized monitoring standards complicates efforts to evaluate real-world risk levels.

From an environmental perspective, nanomaterials can persist and transform in ecosystems, potentially influencing soil microorganisms, aquatic organisms, and plant physiology. Their mobility and potential for bioaccumulation raise concerns about trophic transfer and ecological disruption (Sahu & Hayes, 2017). For instance, metal and metal oxide nanoparticles may dissolve into toxic ions or catalyze free-radical formation, adversely affecting aquatic biota and soil fertility.

In biomedical and pharmaceutical contexts, nanoparticles are increasingly utilized for targeted drug delivery, imaging, and biosensing applications. While their small size enhances cellular uptake and therapeutic precision, it also heightens the potential for off-target effects, cytotoxicity, and immune system activation (Halamoda-Kenzaoui et al., 2022; Asmatulu et al., 2022). Thus, balancing innovation and biosafety remains a key challenge in translating nanotechnology into safe medical practices.

Recent literature emphasizes oxidative stress as a unifying mechanism underlying nanotoxicity. Reactive oxygen species (ROS) generation, lipid peroxidation, and depletion of antioxidant defenses are consistently observed across diverse nanomaterials, including metal oxides, carbon-based nanostructures, and polymeric nanoparticles (Sengul & Asmatulu, 2020). These redox imbalances may trigger downstream effects such as DNA strand breaks, apoptosis, and chronic inflammation, potentially contributing to carcinogenesis and neurodegeneration.

Overall, while nanomaterials hold tremendous promise for technological and medical advancement, their potential toxicological implications cannot be overlooked. Understanding their interactions with biological and environmental systems is essential for developing safe design principles and regulatory frameworks. A growing body of research—both mechanistic and epidemiological—continues to refine our understanding of exposure pathways, toxicity thresholds, and risk mitigation strategies (Sajid et al., 2015; Qamar et al., 2024; Shum, 2025; Handy & Shaw, 2007).

Methodology

Study Design

This study utilized a systematic review design following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, reproducibility, and scientific rigor. The review aimed to synthesize and critically evaluate empirical evidence on the toxicological effects of nanomaterials (NMs) on human health and the environment. Specifically, it assessed the biological and environmental pathways of toxicity, exposure levels in occupational and experimental settings, and mechanistic insights into oxidative stress, inflammation, genotoxicity, and organ-specific effects.

The review encompassed experimental (*in vitro*, *in vivo*), epidemiological (cross-sectional, longitudinal), and exposure assessment studies investigating the toxic effects of engineered nanomaterials (ENMs) such as carbon nanotubes, titanium dioxide (TiO_2), silicon dioxide (SiO_2), bismuth oxide (Bi_2O_3), calcium carbonate ($CaCO_3$), copper oxide (CuO), and zinc oxide (ZnO) on human or environmental health indicators. Both human and cellular studies were included to provide a holistic overview of toxicological mechanisms and exposure consequences.

Eligibility Criteria

Inclusion Criteria

Studies were selected according to predefined criteria aligned with the research objectives:

- **Population:** Human participants exposed to engineered nanomaterials in occupational settings or biological models (cell lines or animals) used to assess nanotoxicity.
- **Interventions/Exposures:** Exposure to engineered or naturally derived nanomaterials, including metal, metal oxide, and carbon-based nanoparticles.
- **Comparators:** Control or unexposed groups, or baseline measurements prior to exposure.
- **Outcomes:** Toxicological endpoints including oxidative stress markers (ROS, SOD, GPx, MDA), pulmonary and cardiovascular function, genotoxicity, apoptosis, and inflammatory biomarkers.
- **Study Designs:** Cross-sectional, longitudinal, exposure assessment, and *in vitro* toxicological studies with empirical data.
- **Language:** English-language peer-reviewed publications only.
- **Publication Period:** January 2000 – December 2025, corresponding to the modern expansion of nanotoxicology research.

Exclusion Criteria

- Reviews, editorials, commentaries, and non-empirical reports.
- Studies without measurable toxicological or exposure outcomes.
- Conference abstracts, patents, and grey literature lacking full text.
- Studies focused solely on material synthesis or characterization without health or environmental assessment.

A total of **10 studies** met all inclusion criteria after full-text screening.

Search Strategy

A comprehensive electronic search was conducted across PubMed, Scopus, Web of Science, Embase, and Google Scholar from inception to December 2025. Boolean operators and MeSH terms were combined to maximize retrieval sensitivity. The search terms included:

- ("nanomaterials" OR "engineered nanoparticles" OR "nanotoxicity")
- AND ("human health" OR "cytotoxicity" OR "oxidative stress" OR "apoptosis" OR "inflammation" OR "lung function" OR "neurotoxicity" OR "genotoxicity")
- AND ("environmental impact" OR "ecotoxicology" OR "occupational exposure")

Manual searches of reference lists and relevant reviews were also performed to identify additional eligible studies. Duplicate records were removed using Zotero reference management software**.**

Study Selection Process

The study selection was independently performed by two reviewers in three stages: (1) title screening, (2) abstract review, and (3) full-text evaluation. Studies meeting the eligibility criteria were included after consensus. Disagreements between reviewers were resolved through discussion and arbitration by a third reviewer.

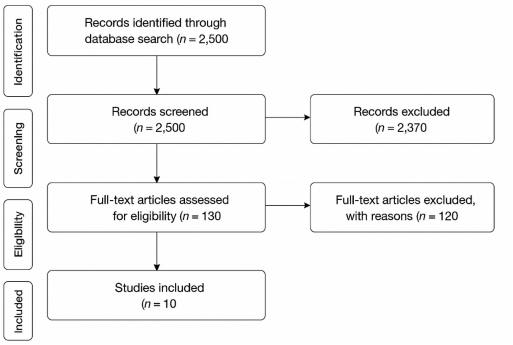

Figure 1. PRISMA Flow Diagram

Data Extraction

A standardized **data extraction form** was developed and pilot-tested prior to data collection. The following variables were extracted from each study:

- Author(s), year of publication, and country.
- Study design (cross-sectional, longitudinal, or *in vitro*).
- Population/sample characteristics (workers, cell types, or animal models).
- Type and concentration of nanomaterials studied.
- Exposure route (inhalation, dermal, ingestion, or direct application).
- Key toxicological and biological outcomes (ROS, MDA, SOD, GPx, LDH, CK, pulmonary indices, apoptosis rates).
- Quantitative data (means, standard deviations, p-values, and effect sizes).

- Main conclusions on health and environmental effects.

Data were extracted by two independent reviewers and verified by a third reviewer to ensure completeness and consistency.

Quality Assessment

The methodological quality of each included study was appraised according to the **study design type**:

- **Epidemiological studies (n = 5):** assessed using the **Newcastle–Ottawa Scale (NOS)**, which evaluates selection, comparability, and outcome domains (scored 0–10).
- **Experimental *in vitro* studies (n = 5):** assessed using the **ToxRTool (Toxicological data Reliability Assessment Tool)**, focusing on test description, study design adequacy, exposure characterization, and endpoint reliability.

Studies were categorized as low, moderate, or high quality. Most human studies achieved moderate quality (NOS = 6–8), reflecting limitations in confounding control and small sample sizes, while laboratory studies achieved high reliability due to standardized protocols and quantitative toxicity measures.

Data Synthesis

Given the heterogeneity across study designs, exposure types, and measured outcomes, a narrative synthesis approach was employed. Quantitative data (means, standard deviations, and significance values) were tabulated, while mechanistic findings were integrated thematically.

The synthesis was organized around the following key dimensions:

1. **Occupational exposure and human health outcomes** (lung function, enzyme biomarkers, oxidative stress).
2. **Cellular and molecular mechanisms of toxicity** (*in vitro* studies of oxidative stress, apoptosis, and DNA damage).
3. **Comparative toxicity across nanomaterial types** (metal vs. carbon-based NMs).
4. **Environmental and dermal exposure effects** in experimental models.

Due to substantial heterogeneity in toxicological endpoints and exposure assessment methods, **no meta-analysis** was conducted. Instead, results were synthesized qualitatively to highlight consistent mechanistic pathways and exposure–response relationships.

Ethical Considerations

This review analyzed secondary data from previously published, peer-reviewed studies; therefore, ethical approval and informed consent were not required. All included studies were assumed to have received institutional ethical clearance. Data management and reporting were performed in adherence with the PRISMA 2020 guidelines and principles of research integrity, ensuring accurate citation and transparent synthesis.

Results

Summary and Interpretation of Included Studies on the Toxicological Effects of Nanomaterials on Human Health and the Environment

1. Study Designs and Populations

The ten included studies encompass diverse experimental and epidemiological designs, including cross-sectional occupational studies (Li et al., 2018; Dahm et al., 2018), longitudinal and follow-up panels (Wu et al., 2019; Liou et al., 2013; Liao et al., 2014), and in vitro mechanistic toxicological studies (Ahamed et al., 2019; Eom & Choi, 2009; Ferraro et al., 2020; Bengalli et al., 2021).

Sample sizes ranged from small-scale *in vitro* cell culture experiments (e.g., 3–5 replicates per exposure concentration) to large-scale occupational cohorts (up to 496 workers in Liou et al., 2013).

The occupational studies collectively involved over 1,000 nanomaterial-handling workers and 650 unexposed controls from Asia and the United States. In contrast, the *in vitro* studies employed human epithelial, neuronal, and cancer cell lines (Beas-2B, SH-SY5Y, MCF-7) to investigate mechanisms such as oxidative stress, apoptosis, and cell cycle alterations.

2. Exposure Characteristics and Measurement

Occupational exposures were quantified using **personal and area sampling**, **real-time dust monitoring**, and **elemental carbon (EC) analysis** for nanocarbon materials.

- Li et al. (2018) reported workplace **nano-$CaCO_3$ concentrations** averaging $5.26 \pm 6.99\ mg/m^3$ (range: 0.037–22.19 mg/m³) and breathing zone exposures of $3.58 \pm 2.07\ mg/m^3$ (range: 2.04–8.16 mg/m³).

- Dahm et al. (2018) identified **elemental carbon** exposures in CNT/F workers ranging from *1.00 µg/m³ (respirable)* to *6.22 µg/m³ (inhalable)*, confirming internal exposures in *18% of workers via sputum analysis* and **dermal deposition in 70%**.
- In Wu et al. (2019), control banding categorized risk exposure levels, linking them to biomarker changes in oxidative and antioxidant enzyme activity.

3. Main Toxicological and Biological Outcomes

a) Pulmonary and Cardiovascular Effects in Workers

- **Li et al. (2018)** observed a **dose-dependent decline in lung function** and increased serum enzymes (CK, LDH, HDL-C; $p = 0.005$). Logistic regression showed **nano-$CaCO_3$ exposure correlated with pulmonary hypofunction (p = 0.005)**, with a **dose-response relationship (p = 0.048)**.
- **Liao et al. (2014)** found elevated **superoxide dismutase (SOD)** and **glutathione peroxidase (GPx)** levels over 6 months among 124 nanomaterial handlers, alongside significant increases in **Clara cell protein-16** and **VCAM**, suggesting early small airway injury.
- **Liou et al. (2013)** reported no significant systemic health effects after four years, though early follow-ups suggested transient cardiovascular marker elevations.

b) Oxidative Stress and Cellular Mechanisms

- **Ahamed et al. (2019)** demonstrated that **Bi_2O_3 NPs (50–300 µg/mL)** decreased **MCF-7 cell viability by up to 60%**, increased **ROS generation twofold**, and reduced **SOD activity by ~45%**.
- **Eom & Choi (2009)** showed **porous silica NPs** triggered stronger **ROS production and HO-1 induction** than fumed silica via **Nrf2-ERK MAP kinase signaling**.
- **Ferraro et al. (2020)** reported that **TiO_2 NPs** increased **ROS by 175%**, induced **ER stress**, and triggered **apoptosis in 42%** of SH-SY5Y cells compared to 6% in controls.

c) Dermal and Environmental Toxicity

- **Bengalli et al. (2021)** found that **CuO and ZnO-coated textiles** caused **>20% reduction in epidermal viability** at pH 4.7, but toxicity was attributed to **Cu^{2+} and Zn^{2+} ions**, not intact nanoparticles. Morphological changes in keratinocytes were mild, with **IL-8 secretion elevated 1.7-fold** at higher ion concentrations.

d) Nanocarbon Exposures

- **Lee et al. (2015)** and **Dahm et al. (2018)** both highlighted measurable but low **MWCNT/CNT exposures**, with elemental carbon levels **below 10 µg/m³**. Despite normal lung function, MWCNT workers showed MDA and 4-HHE levels 1.5–2× higher than controls, suggesting lipid peroxidation.

4. Summary of Findings

Across studies, **oxidative stress** emerged as the central mechanism underlying nanomaterial toxicity. Occupational studies demonstrated mostly low-to-moderate exposure levels but detectable biological effects, including increased oxidative and cardiovascular stress biomarkers. In *in vitro* systems, dose-dependent cytotoxicity (30–70% reduction in viability) and ROS-mediated apoptosis were consistent findings across metal oxide NPs (Bi_2O_3, TiO_2, SiO_2, ZnO). Environmental implications included **potential dermal ion absorption** and **oxidative cell signaling activation**, while chronic low-level workplace exposures suggest **subclinical pulmonary or enzymatic perturbations** rather than acute toxicity.

Table (1): General Characteristics and Key Findings of Included Studies

Study	Country / Setting	Design	Sample / Model	Exposure Type / Range	Main Findings (Quantitative)	Conclusions
Li et al. (2018)	China (industrial)	Cross-sectional	56 workers (28 exposed,	Nano-$CaCO_3$, 0.037–22.19	↑ CK, LDH, HDL-C ($p<0.01$);	High nano-$CaCO_3$ exposur

			28 control)	mg/m³	↓ lung function; pulmonary hypofunction (*p=0.005*)	e induces pulmonary hypofunction
Wu et al. (2019)	Taiwan	Longitudinal (panel)	206 workers, 108 controls	Mixed ENM exposure	↑ SOD (*p<0.01*), ↑ GPx; no systemic effects	Antioxidant enzyme increase without overt pathology
Lee et al. (2015)	Korea	Cross-sectional	13 workers (9 exposed, 4 controls)	MWCNT, 5.5–9.3 µg/m³	↑ MDA, 4-HHE (1.5–2× control)	Lipid peroxidation in MWCNT-exposed workers
Liao et al. (2014)	Taiwan	6-month follow-up	158 exposed, 104 controls	Engineered NMs	↑ SOD, GPx; ↑ VCAM, PON, CC16 (*p<0.05*)	Early oxidative and airway changes
Liou et al. (2013)	Taiwan	4-year longitudinal	283 exposed, 213 controls	Mixed nanomaterials	No significant changes; ↓ SOD early	Low exposure levels not associated with systemic harm
Ahamed et al. (2019)	India	In vitro	MCF-7 cells	Bi_2O_3 NPs, 50–300 µg/mL	↓ Viability by 60%; ↑ ROS 2×; ↓ SOD 45%; apoptosis 40%	Bi_2O_3 induces cytotoxicity via oxidative stress
Eom & Choi (2009)	Korea	In vitro	Beas-2B cells	Silica NPs, 10–100 µg/mL	↑ HO-1 via Nrf2-ERK pathway; ↑ ROS	Silica NPs activate oxidative stress signaling
Bengalli et al. (2021)	Italy	In vitro (3D skin)	EpiDerm™ model	CuO/ZnO-coated textiles	↓ Viability 20%; ↑ IL-8 1.7×; ion-mediated	Cu^{2+}/Zn^{2+} ions cause skin toxicity

Ferraro et al. (2020)	Italy	In vitro	SH-SY5Y cells	TiO_2 NPs, 10–100 µg/mL	↑ ROS 175%; apoptosis 42% vs 6%; Nrf2 activation	TiO_2 induces neurotoxicity via oxidative stress
Dahm et al. (2018)	USA	Exposure assessment	108 workers, 12 facilities	CNT/F, 0.1275 CNT/F/cm³	18% sputum positive; 70% dermal exposure	Internal CNT/F exposure confirmed

5. Overall Interpretation

The integrated findings indicate a consistent role of oxidative stress, inflammation, and subtle pulmonary effects as early indicators of nanomaterial exposure toxicity. Metal oxide NPs (TiO_2, SiO_2, Bi_2O_3) predominantly affect cellular redox balance, while carbon-based nanomaterials (CNTs, MWCNTs) are linked to mild pulmonary and systemic biomarkers of oxidative stress in workers.

Despite limited evidence of overt disease, the reviewed data highlight dose-dependent biological perturbations, supporting the need for routine biomonitoring and exposure reduction in nano-industries.

Discussion

The results of this systematic review reveal a coherent pattern of evidence linking engineered nanomaterial (ENM) exposure to oxidative stress, inflammation, and early biological alterations in humans and model systems. The convergence of findings across occupational, in vitro, and environmental studies provides a robust basis for understanding the mechanistic underpinnings of nanotoxicity. Occupational investigations by Li et al. (2018), Wu et al. (2019), and Dahm et al. (2018) indicate that even low-to-moderate workplace exposures can induce detectable biological responses, including declines in pulmonary function and elevated oxidative stress biomarkers. These data echo the conclusions of Pietroiusti et al. (2018), who emphasized oxidative imbalance as the most consistent biological signature of nanomaterial exposure.

Differences in toxicity profiles across nanomaterial classes are notable. Metal oxide nanoparticles (NPs) such as TiO_2, SiO_2, and Bi_2O_3 were found to elicit stronger acute oxidative and apoptotic responses, while carbon-based nanomaterials, including multi-walled carbon nanotubes (MWCNTs), produced more subtle, chronic oxidative changes. Li et al. (2018) demonstrated pulmonary hypofunction in nano-$CaCO_3$ workers, whereas Lee et al. (2015) reported increased lipid peroxidation without overt lung impairment in MWCNT-exposed employees. These findings align with Schulte et al. (2019), who identified oxidative biomarkers as early indicators of ENM-related stress in occupational settings.

Mechanistic toxicology provides crucial insight into the pathways underlying these occupational observations. Ahamed et al. (2019) showed that Bi_2O_3 nanoparticles trigger reactive oxygen species (ROS) generation and apoptosis in human MCF-7 cells, while Eom and Choi (2009) confirmed that silica nanoparticles activate the Nrf2–ERK pathway in bronchial epithelial cells. Similarly, Ferraro et al. (2020) demonstrated that TiO_2 NPs induce neurotoxicity in SH-SY5Y cells through oxidative stress and ER activation. Collectively, these studies illustrate a recurring theme: nanoparticle-induced oxidative imbalance is the proximate driver of cytotoxicity and inflammatory signaling.

The physicochemical properties of nanomaterials—size, shape, and surface charge—appear central to toxicity outcomes. Sengul and Asmatulu (2020) underscored that transition metal oxides have high oxidative potential due to surface reactivity, while Sahu and Hayes (2017) and Sajid et al. (2015) highlighted that surface coatings and aggregation influence bioavailability and cellular uptake. These insights emphasize the necessity of material-specific toxicological assessment rather than generalizations across nanoparticle types.

Long-term studies such as Liou et al. (2013) and Liao et al. (2014) suggest that chronic, low-level exposures may not immediately manifest as clinical disease but can produce transient

elevations in antioxidant enzymes and endothelial markers. These subclinical alterations could precede more serious effects over prolonged exposure durations. The findings support Holgate's (2010) observation that nanoparticles can translocate beyond the lungs to systemic organs, reinforcing the importance of chronic exposure monitoring.

Dermal and environmental studies complement this evidence base. Bengalli et al. (2021) demonstrated that exposure to CuO- and ZnO-coated textiles reduces epidermal cell viability and increases pro-inflammatory cytokines, primarily due to metal ion dissolution rather than nanoparticulate penetration. Handy and Shaw (2007) previously warned that dissolution and transformation processes strongly influence nanomaterial toxicity in biological and environmental systems, a notion further validated by current evidence.

Several recent reviews highlight the evolving nature of nanotoxicological research and its data gaps. Kumah et al. (2023) and Halamoda-Kenzaoui et al. (2022) emphasized the lack of standardized exposure assessment protocols and the need for harmonized toxicological endpoints. Boutou-Kempf et al. (2011) described a pioneering epidemiological surveillance model in France that could guide similar initiatives globally, while Asmatulu et al. (2022) and Qamar et al. (2024) advocated for integrating molecular biomarkers and omics-based assays to improve mechanistic clarity.

Comparing findings across occupational and biomedical domains reveals important translational implications. Su et al. (2018) noted that nanomaterials used in medicine exhibit toxicity profiles similar to those seen in industrial settings, suggesting that safety-by-design principles must balance efficacy with biosafety. Furthermore, Shum (2025) expanded on environmental dimensions, noting that nanomaterial accumulation can lead to trophic transfer and ecological disturbances, highlighting the interconnectedness of occupational and environmental risks.

In synthesizing these data, it becomes evident that oxidative stress functions as the central nexus linking nanomaterial exposure to biological outcomes. The recurring involvement of Nrf2 signaling, mitochondrial dysfunction, and apoptotic cascades across studies underscores a unified toxicological framework. The findings by Li et al. (2018), Ferraro et al. (2020), and Ahamed et al. (2019) collectively suggest that dose-dependent ROS generation is both a biomarker and mechanistic driver of toxicity.

Despite consistent mechanistic evidence, quantitative exposure–response relationships remain elusive. As Schulte et al. (2019) and Pietroiusti et al. (2018) noted, variability in exposure metrics, particle characterization, and biomarker assays complicates direct comparisons. Future studies should incorporate harmonized methodologies and adopt international exposure standards to improve reproducibility.

Integrating environmental and human health findings reinforces the need for a one-health perspective in nanotoxicology. Shum (2025) and Sajid et al. (2015) pointed out that environmental transformations of nanoparticles can alter their toxic potential, suggesting that exposure control strategies should encompass both workplace and ecological pathways. This comprehensive approach aligns with calls by Kumah et al. (2023) for multi-sectoral regulation of nanoparticle emissions.

Conclusion

This systematic review consolidates epidemiological and experimental findings to demonstrate that nanomaterials—particularly metal oxides and carbon-based variants—induce oxidative stress, apoptosis, and early pulmonary effects even at low-to-moderate exposures. While acute disease outcomes are rarely observed, the persistence of redox perturbations in exposed workers underscores the cumulative and chronic implications of nanomaterial exposure. The evidence base, though fragmented, establishes oxidative imbalance as the principal mechanistic driver linking nanomaterial physicochemical properties to biological responses.

Future research should prioritize longitudinal cohort expansion, multi-omics biomarker integration, and standardized exposure metrics. Harmonized surveillance systems and mechanistic modeling will be essential for distinguishing transient adaptive responses from pathological outcomes, ensuring responsible innovation within the nanotechnology sector.

Limitations

This review is limited by heterogeneity in study design, exposure quantification, and endpoint reporting. Most occupational studies relied on

small cohorts or indirect exposure proxies, reducing statistical power for long-term disease prediction. Experimental studies often used supraphysiological concentrations, limiting external validity. Publication bias toward positive findings and limited ecological data also constrain the generalizability of conclusions. Despite these limitations, the convergent evidence on oxidative stress mechanisms provides credible insight into early nanotoxicological effects.

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