nature reviews earth & environment

https://doi.org/10.1038/s43017-024-00567-5

Review article

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Trends, risks and opportunities in environmental nanotechnology

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Abstract

Engineered nanomaterials (ENMs), intentionally synthesized materials with sizes less than 100 nm in at least one dimension, have numerous potential environmental applications, such as pollution remediation and water treatment. However, concerns regarding their potential health and environmental impacts have been raised. In this Review, we assess the opportunities of ENMs in environmental applications versus their potential public and environmental health risks, focusing on water treatment and reuse, and identify strategies for their responsible use. Life-cycle analyses indicate that the highest potential environmental and health impacts of ENMs used in commercial products are associated with production rather than incidental release during use. Typically, the detected or predicted ENM concentrations are 1 to 4 orders of magnitude lower than their respective predicted no-effect concentrations. In addition, ENMs often undergo passivating transformations, such as agglomeration and oxidation, reducing risks after release. Therefore, the environmental and health risks of ENMs are relatively low. However, some point sources under extreme scenarios, such as sewage effluent, can potentially increase localized risks. Adopting green chemistry and immobilization strategies can further limit the release of ENMs, minimizing their potential discharge into the environment. Such strategies to reduce toxicity and exposure enable sustainable application of ENMs, such that the environmental benefits could outweigh the risks if managed properly.

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Key points

- Environmental applications of nanomaterials include pollution control, green chemistry, clean water production, and sensing and monitoring.
- Despite the potentially substantial environmental benefits of nanotechnology, the large-scale manufacturing requirements, cost limitations and potential health and environmental risks of engineered nanomaterials (ENMs) are common barriers to their widespread use.
- The environmental and health risks of ENMs are relatively low considering the very low ENM concentrations involved and the passivating transformations that occur in the environment, although the potential human health and ecosystem impacts of long-term (months to years) exposure to low ENM concentrations (for example, sub-microgram per litre level in water) remain largely unexplored.
- Life-cycle analyses of ENMs used in commercial products indicate that the highest potential environmental and human health risks are associated with production rather than incidental release.
- To prevent their release into the environment and mitigate exposure, ENMs should be immobilized in or on substrates such as electrodes, membranes and other matrices. Immobilization also enables ENMs to be reused, promoting sustainable and circular practice.
- Additionally, ENM-enabled products and processes should undergo a certification process to meet regulated safety standards to promote best practice and increase social acceptance.

Introduction

Chemical and microbiological pollutants can contribute to the deterioration of water quality, which in turn limits availability of safe water and worsens issues of water scarcity for both humans and ecosystems. Water scarcity is already becoming a concern for numerous regions, such as the western United States and Mexico, and parts of north and east Africa, north China and the Middle East, and will likely worsen due to the impacts of climate change and increasing pollutant loads[1]. Furthermore, there has been insufficient progress towards achieving universal access to safe water and sanitation by 2030 (Sustainable Development Goal 6)[2]. Engineered nanomaterials (ENMs) can be used for both water quality monitoring and water decontamination, and as such could help alleviate water quality and scarcity issues. However, they have had limited commercial applications to date, due to fears that the nanomaterials themselves could pose health or environmental risks.

Nanomaterials are materials with sizes between 1 and 100 nm in at least one dimension. Due to their extraordinary size-dependent properties, ENMs are intentionally designed or synthesized with such structure at the level of individual atoms[3,4] to have specific functionalities, discerning them from the nanomaterials originated from natural processes, such as volcanic eruptions. Numerous ENMs have been developed and exploited for a wide range of applications, including medicine, energy and manufacturing[5–8]. Environmental applications include pollution control[9] (such as nitrous oxide removal[10] and reductive dechlorination[11,12]), clean water production, sensing and monitoring, and green chemistry[10,13–15]. For example, nano zero-valent iron has been applied for groundwater remediation to remove pesticides and heavy metals[16]. The promise of ENMs to enable many environmental technologies and the need to assess and mitigate associated life-cycle risks have since defined the field of environmental nanotechnology, a highly multidisciplinary field that seeks to apply nanotechnology as a tool for sustainability without becoming an environmental liability.

In the early 1990s, the increasing production of ENMs and their rapid incorporation into consumer products and industrial processes seemed to outpace the development of appropriate knowledge about potential unintended consequences[17]. There was growing concern about nanotechnology generating a new class of pollutants[18–20] with associated risks to public and environmental health[21,22], such as pulmonary toxicity of inhaled ultrafine (nano-sized) particles[23–25]. Research on ENM toxicity quickly responded to such concerns, reflecting an impetus for proactive risk assessment, which presents an important contrast to the 20–30-year lag in the toxicological literature following the increased use of asbestos[26,27] (Fig. 1). The potential environmental impacts of ENMs, together with their environmental applications, have been comprehensively reviewed[8,13,14,28]. However, the potential for acute cytotoxicity and genotoxicity of several ENMs was sometimes reported from experiments conducted using unrealistic short-term exposures to very high concentrations of pristine ENMs in suspension, which can lead to acute toxicity responses[29]. Since then, much lower acute toxicity has been reported from experiments conducted under more realistic conditions, for example, by considering interactions of ENMs with environmental matrices that decrease their reactivity, bioavailability and toxicity[30–32]. Overall, the evolution of environmental nanotechnology experienced an early research hype driven by risk assessment under considerable uncertainty, followed by an ambitious exploration of ENM applications for a wide range of environmental challenges (Fig. 2). The fundamental knowledge gained by researching potential public and environmental health impacts is now facilitating the development of safer and more sustainable nanotechnology for environmental applications, many of which relate to water treatment and reuse[10,33–35].

In this Review, we explore the trade-offs between the risks and benefits of environmental nanotechnology (from implications to applications) from a life-cycle perspective, with the aim to balance safety and sustainability concerns with the potential societal benefits of technological ENM innovation. We summarize the state of knowledge about ENMs and nanotechnology-enabled processes that are being considered for the most promising water treatment and reuse applications. We also explore strategies for the responsible use of environmental nanotechnology, such as improvements in ENM design and immobilization to help mitigate their release and minimize exposure. Finally, we propose strategies and research priorities for the sustainable development and use of environmental ENMs, many of which are relevant to the nanotechnology industry more broadly.

Environmental technologies with ENMs

The interest in ENMs for various applications originated from their unique characteristics, which strongly depend on their size, shape, nanoscale structure and elemental composition. The extremely small size of ENMs leads to high specific surface area, high reactivity and unique electronic, photonic and superparamagnetic characteristics resulting from the quantum effect[36,37]. The structure and shape of ENMs are also important, influencing their mechanical, chemical, electronic and tribological properties[38,39]. Therefore, ENMs have been widely applied in various applications such as medical, energy and personal care products. According to the Nanotechnology Consumer Products

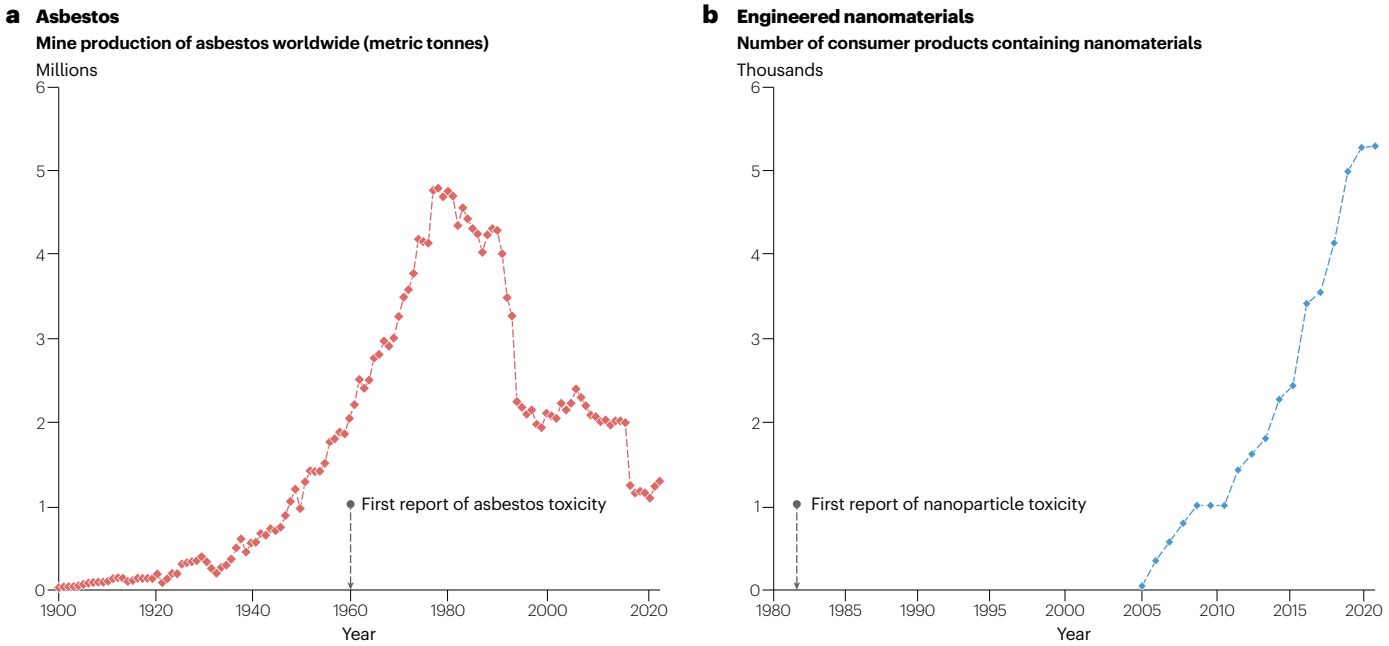


Fig. 1 | Links between toxicology research activity and worldwide use of asbestos and ENMs. a, A lag of 20–30 years occurred between the first report of asbestos toxicity in the 1960s and the decline in asbestos production in the 1990s, reflecting the relatively long time it took to recognize asbestos as the main cause of mesothelioma and asbestosis[26]. **b**, By contrast, for engineered nanomaterials (ENMs) there was an approximately 20-year delay after the first reports of toxicity in the 1980s (ref. 27) before there was an increase in the number of products containing ENMs. The difference between asbestos and ENMs reflects an impetus for proactive risk assessment of ENMs.

Inventory, ENM-enabled commercial products are mostly categorized in health and fitness products[40]. Moreover, the extraordinary properties of ENMs have inspired exploration of their potential in a myriad of environmental applications, including pollution control, sensing and monitoring, green chemistry and clean water production[10,13–15], which are discussed in this section.

Environmental applications of ENMs

ENMs have been considered for water treatment, soil remediation and air pollution control applications as they can provide a huge surface area and active sites for adsorption and (photo)catalytic oxidation[13,41,42] or reduction[43–45] of various pollutants (such as volatile organic compounds). ENMs can be used in membrane separation[46–48] and disinfection processes during water treatment and reuse[33,49,50]. During their development in the early 2000s, relatively simple ENMs were tested for these applications, including metal, metal oxides, carbon-based nanomaterials (such as graphene or graphene oxide (GO)) and polymeric nanoparticles, as they had well-defined, specific functionalities[51] and unique size-dependent properties. However, many ENM-enabled technologies remain at the early development stage[52] in laboratories because of the limitations in large-scale manufacturing and cost-effectiveness. Commercial application has only been achieved for small-scale water treatment devices and air purifiers for a small number of ENMs, including silver nanoparticles (AgNPs), iron or iron oxide nanoparticles, titanium dioxide nanoparticles ($nTiO_2$) and zirconium dioxide nanoparticles, aquaporin and some carbonaceous ENMs (such as carbon nanofibres and carbon black nanoparticles). Translating exciting scientific discoveries from the laboratory to practical environmental technologies faces substantial challenges.

Increasingly, environmental nanotechnology research explores the multifunctionality of hybrid ENMs or nanocomposites. Hybrid ENMs and nanocomposites consist of one or more nano-sized components arranged in configurations (such as core–shell, sandwich and mixed matrix) that favour synergism between functions of individual nano components (Fig. 3). For example, the rational design of a composite material might aim to create synergy between selective proximal adsorption and catalytic degradation of recalcitrant pollutants (such as perfluorooctanoic acid and perfluorooctyl sulfonate), while maintaining desired bulk material properties conducive to the treatment process (such as electroconductivity for an electrochemical process and water permeability for membrane separation).

ENMs that provide precise multidimensional pore structures with tunable chemistry have garnered increasing interest for precision separation and selective contaminant removal (Fig. 3). These ENMs include metal–organic frameworks, covalent organic frameworks, GO, molybdenum disulfide, transition metal dichalcogenides, transition metal carbides and nitrides[53]. Nanoscale 2D or 3D pore structures of these ENMs provide immense surface area and pore volume for pollutant adsorption. For example, multidimensional ENMs have the capacity to adsorb heavy metals and organic contaminants several times higher than their own weight[54,55]. More importantly, their surfaces can be easily functionalized with ligands to tune the pore size and surface chemistry of the pore walls, providing a highly tunable coordination environment for selective binding of target pollutants[56,57]. The nanoporous structure also allows easy incorporation of other ENMs to endow additional functions such as magnetic separation[58], visible light photocatalytic activity[59], electrical conductivity and sensing[60] in the composite material.

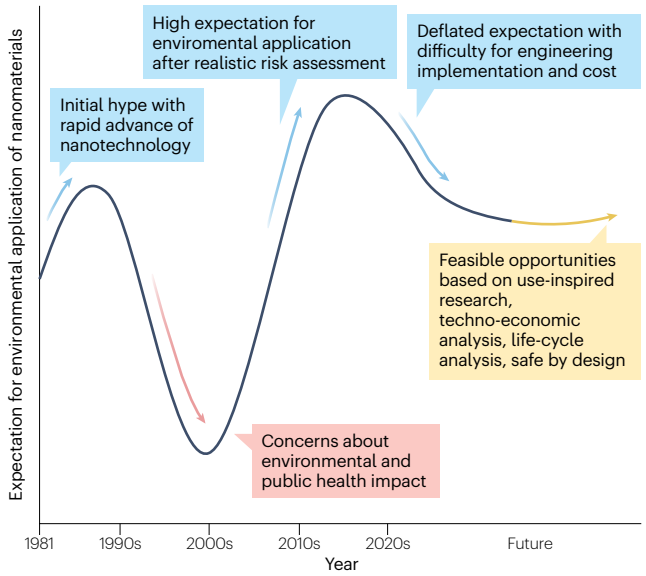


Fig. 2 | Research priorities and expectations of environmental applications of nanotechnology over time. Research priorities (safety concerns versus expected benefits) of engineered nanomaterials (ENMs) have evolved over time from an overly optimistic outlook on their potential to a fear of nanotoxicity; then to a more realistic understanding of safety concerns, and to increased ability for efficient and safe use of nanotechnology.

Considerations for large-scale applications

Whereas several ENMs are already manufactured at commercial scales (such as AgNPs, $nTiO_2$, iron or iron oxide nanoparticles and carbon nanotubes (CNTs)), they are mostly applied in antimicrobial and cosmetic products and coatings and additives[52]. Environmental applications of most ENMs remain largely a topic of laboratory research. A notable barrier is the economical manufacturing of ENMs or ENM-enabled functional materials for large-scale applications. For example, a mono-atomic layer of graphene with sub-nanometre pores is an ideal membrane which allows desalination with ultra-high permeability and selectivity[15]; however, it is not yet possible to fabricate such a membrane at a size sufficient for even small-scale applications. Instead, a multilayer assembly of GO nanosheets with well-controlled interlayer spacing is a more technically feasible approach to achieve a free-standing semi-permeable membrane suitable for commercial-scale desalination projects[15]. The challenge remains that a large number of layers are needed to minimize transport through defects; such as gaps between adjacent nanosheets on the same horizontal plane[15,61,62], which reduces membrane permeability. Similarly, the synthesis of multifunctional ENMs is still complex and expensive, limiting their application to small-scale, high added-value uses, such as sensing[63] and green energy production[7]. Thus, the cost-effectiveness of ENMs needs to be judiciously evaluated on a case by case basis.

The long-term stability and activity of ENMs in the receiving medium is another important consideration. For example, GO stacks expand over time in water, leading to eventual dispersion of the GO nanosheets. Another example is that the adsorption of target contaminants on metal–organic frameworks through ion or ligand exchange can result in structural changes of the metal–organic framework[64]. In addition, the presence of background interfering species can reduce the adsorption capacity as well as poison nanocatalysts; fouling and scaling caused by various chemical and biological species can also passivate ENM surface active sites[65]. Such consideration is even more critical for soil and groundwater remediation, as the ENMs need to migrate through the subsurface to reach the target contaminants[66]. For example, the limited mobility of nano zero-valent iron poses a major challenge for its practical applications in groundwater remediation[66,67]. Therefore, modifications such as coatings or supports have been developed to enhance the mobility and selective reactivity of nano-zero valent iron[68].

Environmental factors also need to be considered because of their strong effect on the performance of ENMs. For example, quantum dots with photoluminescence have been shown to detect heavy metals (such as mercury, lead and chromium), organic contaminants and pathogens, with high selectivity and sensitivity[69,70]. Yet robust performance in practical water sensing applications is still questionable as the optical properties of the quantum dots are strongly affected by water quality[13,71]. In comparison, electro-based processes enhanced by ENMs could be a more reliable way to deliver redox reactions than other advanced oxidation processes for degradation of recalcitrant organic pollutants and disinfection[72]; here, the challenge lies in the long-term stability and activity of ENMs in redox active environments. For water treatment applications, important factors include sunlight, temperature and the physicochemical properties of water such as turbidity, pH and the presence of interfering species. For soil remediation and groundwater treatment, soil properties (such as porosity, hydraulic conductivity and organic contents) need to be considered. Nevertheless, for ENMs with scale-up capabilities, cost-effectiveness must outcompete conventional treatment strategies to gain adoption. Therefore, problems that conventional methods cannot solve are ideal first applications for ENMs.

Overall, the unique size-dependent properties of ENMs enable the development of novel materials and technologies that offer substantial advantages for environmental applications. These include hybrid ENMs or nanocomposites with multifunctionality and novel ENMs with precise and tunable pore structure, which are receiving growing attention. When developing ENM-enabled materials or processes for environmental applications, several factors should be considered, including the materials' long-term stability and activity, environmental factors that affect performance, large-scale manufacturing capability and cost.

Transport, transformation and fate of ENMs

In the environment, released ENMs undergo various physical and chemical processes which either passivate or activate the ENMs. These processes are generally agglomeration and aggregation, deposition, surface reactions (chelation and oxidation), dissolution and bioaccumulation. Mostly, the toxicity and reactivity of ENMs are largely passivated by these processes.

Accurate prediction of the concentration, morphology and reactivity of ENMs that are accidentally or incidentally released into the environment remains an elusive goal due to the highly complex system-specific and ENM-specific factors that influence ENM transformations, reactivity, transport and bioavailability. In the aqueous phase, ENMs often exhibit a tendency to aggregate, agglomerate or deposit on surfaces. These physical processes are similar to those extensively studied for colloidal particles, for which advection–dispersion and filtration models have been developed and validated. These models can be easily adapted to obtain first approximations of ENM transport in

water systems. More difficult to predict are system-specific processes that transform ENMs or modify their surfaces and aggregation states, and subsequent reactivity (Fig. 4). These processes include dissolution and subsequent speciation changes, redox reactions (oxidation and sulfidation), photochemical reactions and corona formation. The rate and extent of these transformations are a function of both initial ENM properties (such as size, elemental composition, surface energy and specific surface area) and environmental factors (such as redox conditions, pH, type and concentration of natural ligands, types of surfaces and microbial activity), and the complexity and variability of the latter make accurate predictions extremely difficult. Another major limitation in environmental fate and transport models for ENMs remains the lack of adequate input data for model calibration and validation[73].

Research on ENM fate, transport and impact has evolved from simple, reductionist experiments towards more holistic studies that consider increasing complexity. Early research on this topic was primarily conducted with pristine nanoparticles suspended in well-defined systems[74], and progressed to consider hybrid ENMs in more realistic natural systems, including coatings (both manufactured or naturally acquired) and surface modifications[75–77]. Currently, a more comprehensive approach that considers the life cycle of nano-enabled products (NEPs) has been adopted, including the release, transformation and fate of NEP residue after ageing and other alterations[78–81]. Whereas such increasing research complexity generally minimizes experimental artefacts and generates more realistic empirical results, discerning underlying mechanisms and unifying principles becomes more challenging. Nevertheless, some general heuristic trends can be discerned.

The ENM aggregation (including heteroaggregation) rate increases with the ionic strength and divalent cation (such as calcium and magnesium) concentrations and decreases in the presence of natural organic matter (NOM). Importantly, suspended aggregates tend to be less bioavailable and less toxic to planktonic organisms and filter-feeders than pristine ENMs due to their lower specific surface area and slower dissolution rate[82,83]. For example, heteroaggregation between Al_2O_3 particles and GO mitigated toxicity of GO to the freshwater algae *Chlorella pyrenoidosa* by inhibiting the physical contact between algae and GO, decreasing oxidative stress (as indicated by a decreased concentration of reactive oxygen species)[82]. However, aggregates that settle down tend to accumulate in sediments and be more bioavailable and potentially toxic for benthic organisms in aquatic systems, as observed with zinc oxide nanoparticles (nZnO)–clay heteroaggregates[32,84]. In the case of photosensitizing ENMs such as fullerenes[85], aggregation leads to triplet–triplet annihilation, which also decreases reactivity and toxicity. A notable exception is CNTs: aggregated CNTs might offer multiple harmful contacts with bacteria and induce increased cytotoxicity compared with dispersed CNTs[86,87].

Highly reactive materials with high surface energy (such as high facet-energy CdS nanorods, nano zero-valent iron, photosensitive AgNPs, $nTiO_2$ and carbon nanomaterials) tend to react quickly with environmental constituents and therefore experience rapid passivation, lowering their risk[88,89]. It is noted that short-term solar irradiation could increase toxicity of GO towards aquatic organisms due to the formation of smaller GO flakes, low molecular weight degradation products and enhanced conductivity[90–92]. However, other chemical species present in water (such as Cu^{2+}) could suppress the phototransformation of GO[93]. Long-term irradiation (for example, over months) could also lead to further GO degradation that reduces its toxicity[92,94].

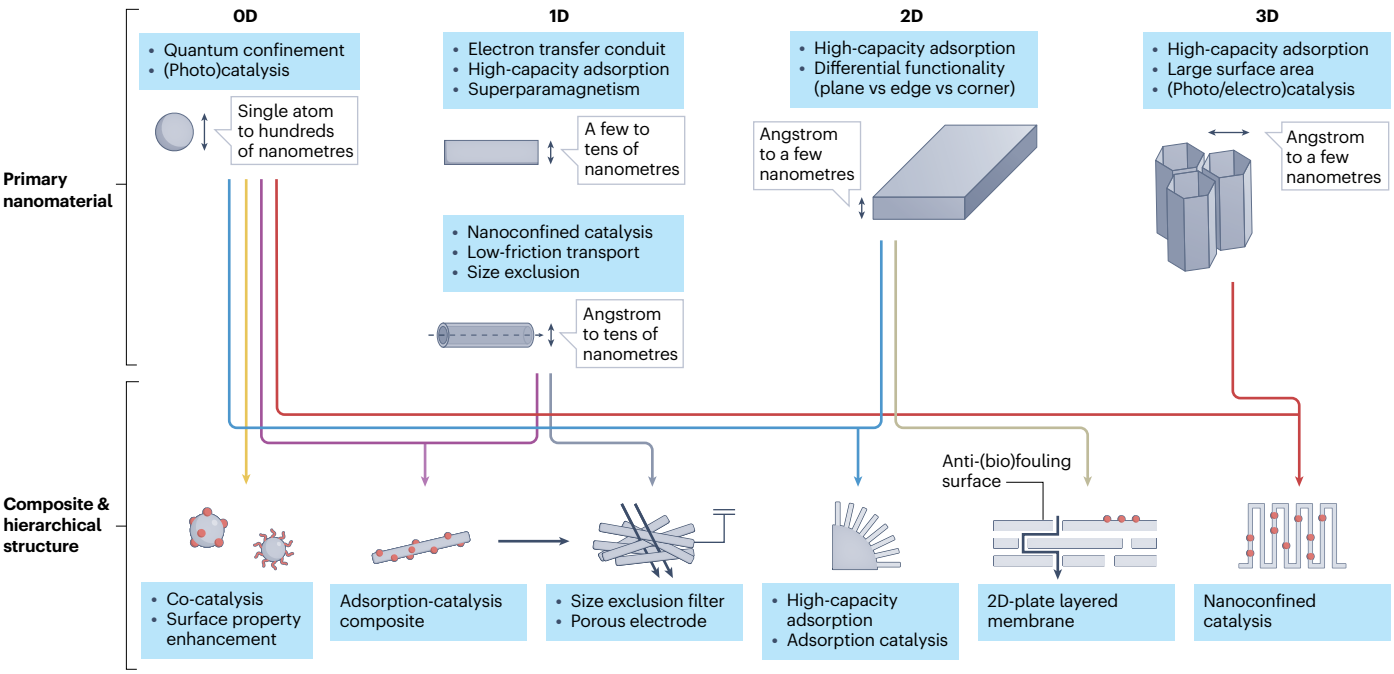


Fig. 3 | Potential environmental applications of various types of ENMs. Progression in the design of primary nanomaterials to higher dimensions and towards more complex composite materials has enhanced their efficiency for water treatment applications. Different primary nanomaterial forms were the starting products for more complex composite and hierarchical nanomaterial structures (coloured arrows). Composite and hierarchical structures can incorporate selective proximal adsorption and catalytic degradation properties while maintaining the desired bulk material and engineered nanomaterial (ENM) properties. Red dots represent 0D nanoparticles that are imbedded in or on the substrates.

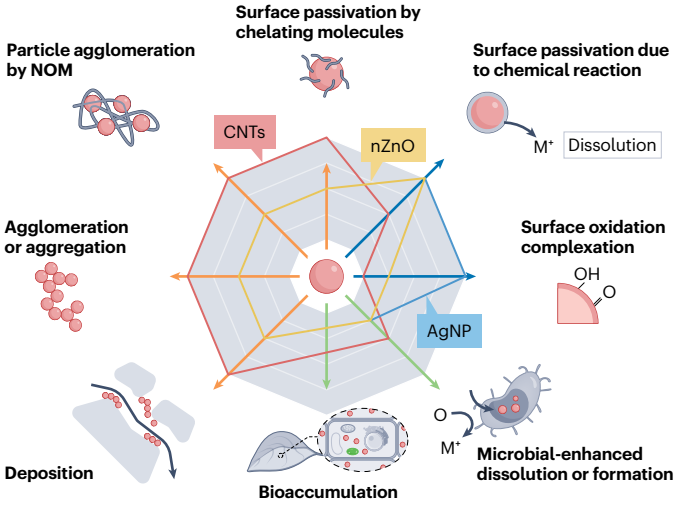


Fig. 4 | Processes affecting the transport, transformation and fate of ENMs in the environment. Transport and transformation of engineered nanomaterials (ENMs) in the environment are affected by important physical (orange arrows), chemical (blue arrows) and biological (green arrows) processes, which can enhance or mitigate the concentration, reactivity and toxicity of ENMs. Example processes are shown in diagrams around the edge of the plot. The corresponding relative importance of each process (except bioaccumulation) on the fate of silver nanoparticles (AgNPs; blue lines), zinc oxide nanoparticles (nZnO; yellow lines) and carbon nanotubes (CNTs; red lines)[232] is indicated by the intercepting points between each ENM's data line and the coloured arrows (where outer portions of the plot represent greater importance, and inner portions lesser importance). Mostly, transport and transformation processes lead to the passivation of ENMs. NOM, natural organic matter.

For many metallic ENMs such as quantum dots (for example, quantum dots with CdSe cores and ZnS shells, CdSe/ZnS)[95], AgNPs[96] and nZnO[97], toxicity is largely attributed to their dissolution and subsequent release of metal ions. In contrast, carbon nanomaterials and some inorganic ENMs such as CeO_2 nanoparticles and $nTiO_2$ exhibit very low solubility; their dissolution is less important from a toxicological perspective but could be of greater long-term concern from a regulatory perspective[98].

Adsorption of NOM and proteins that form coronas on the ENM surface[20,99], sulfidation of metallic nanoparticles[100,101] in an anaerobic environment and formation of oxides or hydroxides[102,103] under aerobic conditions are common surface passivation mechanisms that decrease metal dissolution and, thus, toxicity[104].

Depending on environmental conditions and microbial community structure, bacteria can increase (by decreasing pH through acid production) or decrease (by coating ENMs with a corona of protein or soluble microbial products) dissolution of metallic ENMs, and even form nanoparticles (as a defence mechanism against toxic metal ions, mediated by surface saccharides)[105,106].

Quantitative understanding of these transport and transformation processes is important not only for risk assessment but also for mitigating passivation of ENMs in engineered systems and enhancing their long-term performance. For example, ENM immobilization on a solid substrate can be an effective strategy to mitigate exposure to ENMs that could otherwise escape the engineered system, as well as to mitigate particle aggregation and the associated decrease in reactivity[85]. Adequately dispersing the ENM on the substrate while minimizing surface passivation is important to prevent loss of ENM reactivity. Another example of applying insight from fate and transport studies is the partial sulfidation of AgNPs (used in anti-biofouling coatings) to control the Ag^+ ion release rate, which is the critical effector of antimicrobial activity[96] and thus prevents rapid depletion of silver[107]. Similarly, reactive nanoparticles with a porous outer shell can be used to control the reaction rate and limit competition by interfering species (such as NOM) larger than the pores in the shell[108,109].

In sum, ENMs that are accidentally or incidentally released into the environment will experience multiple processes that generally decrease their mobility and passivate their reactivity and toxicity. The quantitative understanding of the transport and transformation processes of ENMs is important to accurately quantify and predict their environmental fate and potential risks.

Potential environmental impacts of ENMs

The properties of several ENMs raised early concerns regarding potential risks to public and environmental health. As the risk is the product of hazard and exposure, a life-cycle perspective is necessary to objectively evaluate the environmental impact of ENMs, which takes both the toxicity and potential exposure of ENMs into consideration. This section discusses the mechanistic toxicity of ENMs, identifies the potential release pathways and quantitatively assesses the risks of ENMs.

Toxicity versus exposure

Toxicity studies showed that the small size of ENMs could increase their chance of penetrating cell membranes[110] and translocating to different organelles, which could lead (in a dose-dependent manner) to oxidative stress and disruption of gene expression, possibly affecting physiological activities at sufficiently high doses[29]. The nanoscale size might also induce localized mechanical stress leading to disruption of cell integrity. Metal ions released from some ENMs and their catalytic reactivity were shown to cause cytotoxicity and genotoxicity mainly due to excessive reactive oxygen species generation as an induced cellular response[111].

The shape-related and structure-related toxicity are more notable at high doses of 1D ENMs, exhibiting fibre toxicity similar to that of asbestos[30]. However, early research put much more emphasis on toxicity than on exposure, both of which are required to pose a risk. The exposure of ENMs is associated with their incidental or accidental releases during environmental and other applications. In many toxicity studies, very high exposure levels (for example, ENM doses at milligram per litre to sub-gram per litre levels) were used, resulting in an exaggeration of the potential risks of ENMs in the environment[30,31,112]. Fate and transport studies that took into consideration ENM interactions with different environmental components, however, identified immobilization and/or passivation processes that lead to very low potential exposure[17,65,113,114]. Additionally, immobilization strategies are commonly implemented for ENM applications and reuse in water treatment which mitigate their release and potential adverse impacts.

ENM release into the environment

The National Nanotechnology Initiative in the United States published a seminal strategy for environmental health and safety research in 2011. The strategy underscored the importance of a life-cycle perspective in evaluating the risks and benefits of ENMs, accounting for both accidental and intentional ENM release into the environment over the life cycle of NEPs from their production, assembly, use and disposal[115,116] (Fig. 5).

The annual production of ENMs is estimated at about 10^6 tons per year based on literature data from 2012 to 2016, and silicon dioxide nanoparticles ($nSiO_2$), $nTiO_2$ and nano-clays are produced in the highest quantities[52,117]. However, the quantity of ENMs is insignificant and almost negligible (<0.1%) in the global cycles of nano-sized materials, which is dominated by nanomaterials of natural origin[118,119]. Moreover, in the context of global cycles of different elements, ENMs account for less than 2% of the elements being mined (Fig. 5), except for silicon-based ENMs which make up 3–25%[52] of the global silicon cycle.

Quantifying emissions from use requires understanding how various ENMs are used in products and other end uses, and quantifying their loss through mechanisms such as abrasion, photodegradation of nano-composite matrices and dissolution. For some applications (such as nanopesticides and soil remediation), ENMs are directly released

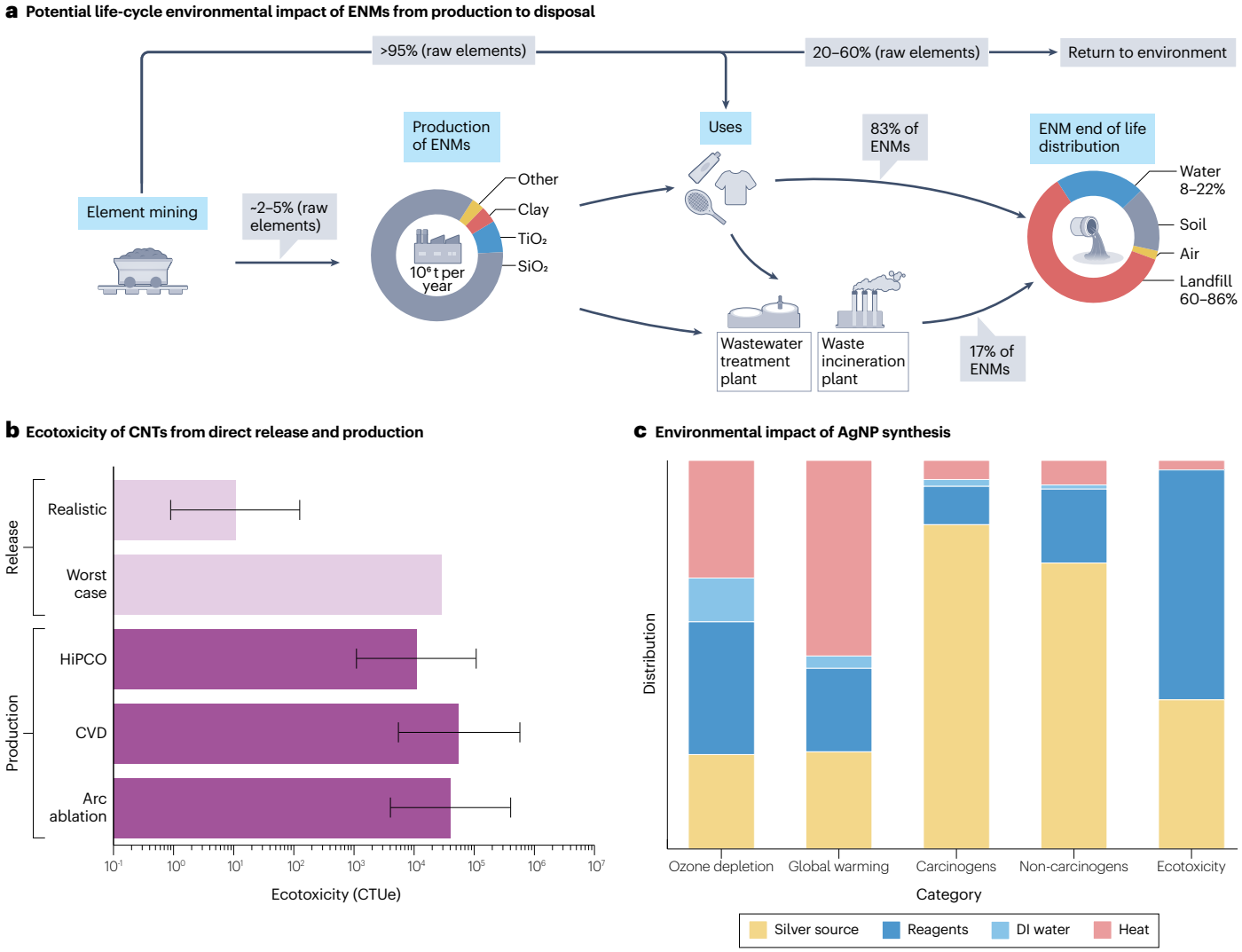


Fig. 5 | Potential environmental impact of ENMs across the life cycle from production to disposal. a, Global flow of engineered nanomaterials (ENMs) from raw element mining, manufacturing and usage to end-of-life disposal[52,117,147,160,161]. Only 2–5% of mined elements are manufactured into ENMs. Annual production of ENMs is estimated at about 10^6 tons per year based on literature data from 2012 to 2016, and silicon dioxide nanoparticles ($nSiO_2$), titanium dioxide nanoparticles ($nTiO_2$) and nano-clays are produced in the highest quantities[52,117]. Most ENMs (~83% of the ENMs) are directly released from user products to different environmental compartments. Most ENMs end up in landfills (60–86%), followed by water (8–22%), soil and air[147]. Data from refs. 52,115,147. **b**, Potential ecotoxicity of direct release versus production of carbon nanotubes (CNTs). Ecotoxicity is characterized by comparative toxic units (CTUe) using different methods[160]. The plot shows that the ecotoxicity of production is generally higher than that of release (except in some worst-case release scenarios). Error bars represent the standard deviation. **c**, Potential environmental impact of silver nanoparticle (AgNP) production[161], including contributions to ozone depletion, global warming, carcinogens, non-carcinogens and ecotoxicity. The chemical feedstocks, including the silver source material (yellow) and reagents (blue), cause the majority of impacts in all cases except for global warming, where heating (red) is the main contributor. Production activities have higher potential impacts than realistic release scenarios, and the feedstock for ENM production accounts for most of the environmental impacts. CVD, chemical vapour deposition; HiPCO, high-pressure carbon monoxide; DI water, deionized water. Panel **b** adapted with permission from ref. 160. Panel **c** adapted with permission from ref. 161.

into the environment, but for others (such as textiles and plastic containers) ENMs undergo transformations before their environmental release. Early experiments tested pristine ENMs in highly controlled conditions, but later research recognized that ENMs can undergo various transformations when being incorporated into products and subsequently weather, and that ENMs released from actual products differ in morphology and chemistry from the pristine form[120]. Extensive experimental research on ENM release during use was conducted on a wide range of consumer and building products including textiles, plastics, epoxy-based coatings and cementitious materials[121–125].

ENM release scenarios in water treatment and reuse applications also involve ENM transformations. Relatively few water treatment applications consider the use of suspended or dispersed ENMs (such as quantum dots for sensing pathogens[70], nano zero-valent iron for reducing chlorinated solvents in groundwater[68,126] and $nTiO_2$ or hexagonal boron nitride for photocatalytic degradation and disinfection[108,127–129]). Instead, ENMs are generally immobilized in or on a substrate or treatment device (such as reverse osmosis membranes impregnated with AgNPs for biofouling resistance[130,131]). Thus, the chemical nature of the substrate (such as polymeric or inorganic), its structure (including porosity) and its durability need to be considered to assess ENM release, fate and potential impact[79,132]. For example, a mesocosm study showed that the stability and fate of copper nanoparticles (nCuO) and their toxicity to freshwater organisms depended on the life-cycle stage of the matrix that nCuO are embedded in — an antifouling wood stain in this case[79]. Pristine nCuO that can be released during the production stage of this wood stain were more bioavailable and potentially more toxic (due to higher release of Cu^{2+} ions) than stain fragments released during the use and end-of-life stages. Furthermore, unlike pristine nCuO that primarily impacted planktonic organisms, the stain fragments products experienced fast aggregation and settling, exposing primarily benthic organisms[79]. Therefore, the life-cycle dynamics of the entire NEP including ageing and other alterations, rather than ENMs alone, should be considered for risk assessment[133].

ENM release from water treatment materials and devices is relatively less studied. To date, the most studied ENMs are AgNPs. Release of ENMs into the environment is strongly dependent on experimental conditions, such as operational hydrodynamics and water quality (such as pH, temperature, salinity, presence of other ions and NOM)[134–137]. For example, although Ag^+ and/or AgNPs were released from AgNP-impregnated reverse osmosis membranes under different operational conditions, the total silver concentration in the receiving water was below the secondary maximum contaminant levels of 0.1 mg L^{-1} set by the US Environmental Protection Agency (EPA), except under batch immersion, which was not a common use scenario. Moreover, much less silver was released in dead-end filtration than in cross-flow filtration[134]. In another study, the total silver concentration in the permeate after dead-end filtration with a filter paper containing AgNPs exceeded 0.1 mg L^{-1} at the beginning; and deionized water and seawater led to a much higher silver release than surface water[135]. Therefore, ENM release from water treatment devices and the subsequent potential risk need to be assessed on a case by case basis. Additionally, the synthesis or incorporation methods[138] of ENMs in the matrix influence the release behaviour, highlighting the importance of safety by design strategies for environmental applications of ENMs to mitigate risk, as discussed in the next section.

Municipal wastewater treatment plants are important locations where ENMs released from product uses can occur. ENM removal by municipal wastewater treatment processes and occurrence in wastewater effluent and sludge have been studied[139]. Potential unintended consequences related to wastewater treatment processes, such as enhanced antimicrobial resistance[140] and formation of disinfection by-products[141], have also been considered. Combining measured partitioning coefficients with expected loading rates in influents allowed for estimation of ENM concentrations in wastewater effluents and receiving water bodies. More broadly, multimedia probabilistic material flow[142] or mechanistic box models such as SimpleBox4nano[143] were constructed to assess ENM flows over their life cycle and subsequent fate and transport among environmental compartments.

Quantifying environmental risk

Comparisons of measured environmental concentrations (MECs) and predicted environmental concentrations (PECs) with predicted no-effect concentrations (PNECs) from toxicological studies have been used to assess the environmental risk of ENMs. The risk characterization ratio (RCR), simply defined as the PEC to PNEC ratio, is commonly used as a quantitative indicator of ENM environmental risk.

Reported MECs of different ENMs are typically several orders of magnitude lower than PNECs in surface water, air, sediment and soil (Fig. 6a), with the exception of two seawater samples that showed measured concentrations of AgNP and $nTiO_2$ higher than their respective PNEC[144] (Fig. 6b). However, the MECs reported here did not distinguish nanomaterials of engineered or natural origins. Similarly, 90% of reported RCR values for these natural environmental compartments, mostly calculated using PECs instead of MECs, are much lower than one (Fig. 6b). A few exceptions are where extreme scenarios were considered for PEC calculation[142] and in waters close to treatment plant outfalls[115,117] (Fig. 6). These data suggest that ENMs are generally of no to low risk to the natural environments. By contrast, MECs higher than PNECs or RCR values greater than one were reported for multiple ENMs in sewage samples[142,145–149], suggesting that potential environmental risks of ENMs should be considered when discharging or reusing municipal wastewater. However, it should be noted that the scarcity of ecotoxicity data and the PNEC's high sensitivity to the quantity and quality of toxicity data[150] means, potentially, very high uncertainty in the PNEC values. As different toxicity studies have used ENMs with different properties (size, shape and surface energy) and different experimental conditions, this further complicates the determination of PNECs. Reported PNEC values of AgNPs, $nTiO_2$ and CNTs vary by two orders of magnitude across different studies[31,151–153]. In addition, variability in PECs is also very large, spanning five orders of magnitude between the lower and upper limits in some cases (Fig. 6a) due to uncertainties in production volumes and other model assumptions. Therefore, risk assessment using the RCR remains a challenging task.

Overall, potential risks to human health via drinking water consumption are low. In water bodies that supply drinking water treatment plants, PECs for ENMs reported so far are orders of magnitude lower than concentrations of natural nanoparticles; treatment processes designed to remove particles also remove ENMs effectively[154]. Similarly, risks posed by ENMs in soil are low, as the current PECs of ENMs are two to five orders of magnitude lower than their PNECs. Note that only iron-based ENMs (such as nano zero-valent iron) have been applied for contaminated soil and aquifer remediation, and iron is a naturally abundant element that is generally considered safe. Although PECs of various ENMs in sediments can be orders of magnitude higher than in other environmental compartments, the potential risks to the related organisms (such as aquatic benthos) should also be low, as many ENMs undergo physical (such as aggregation) and chemical (such as

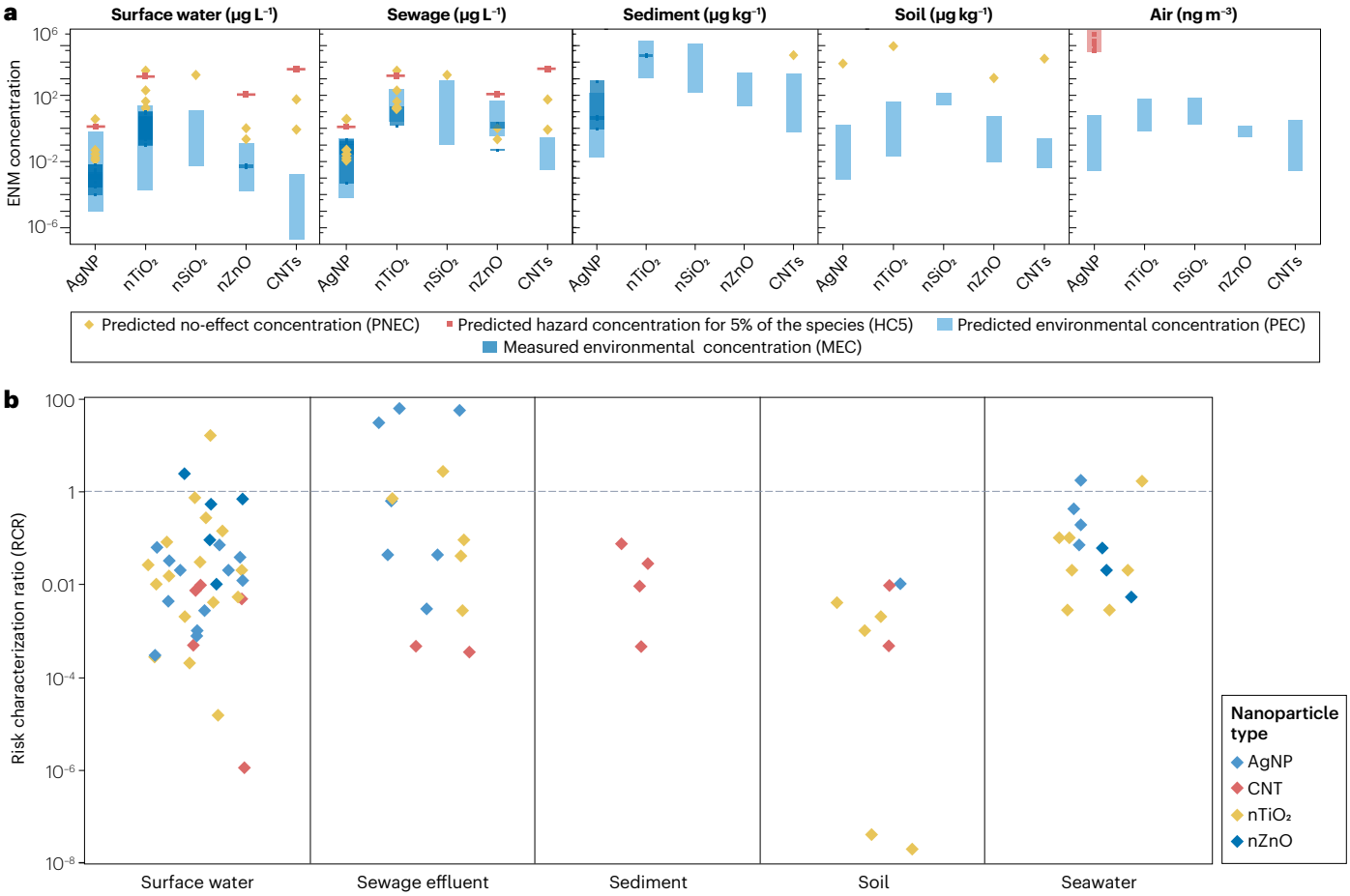


Fig. 6 | Concentrations and risk characterization ratios of selected ENMs. **a**, Selected engineered nanomaterial (ENM) concentrations for different environmental compartments[31,79,117,142,147,152,154,233–236], including surface water, sewage, sediment, soil and air. Concentrations are reported as predicted environmental concentrations (PECs; light blue boxes), measured environmental concentrations (MECs; dark blue boxes), predicted hazard concentration for 5% of the species (HC5; red lines) and predicted no-effect concentrations (PNECs; yellow diamonds). **b**, Risk characterization ratios (RCRs) for the same environmental compartments, which is the PEC to PNEC ratio of a specific ENM[73,144,151,152,236,237]. RCR > 1 indicates high risk of ENM (above the horizonal dashed line). RCR is far below 1 in 90% of reported data across the different environmental compartments. As such, ENMs generally pose little risk in these different environmental compartments in most situations, as their concentrations are well below the corresponding PNECs. However, ENMs in sewage effluent show higher potential risk. AgNP, silver nanoparticle; CNT, carbon nanotube; $nSiO_2$, silicon dioxide nanoparticles; $nTiO_2$, titanium dioxide nanoparticles; nZnO, zinc oxide nanoparticles.

sulfidation) transformations in the environment that render them less toxic than their pristine, well-dispersed forms[155]. For example, negligible toxicity of AgNPs and TiO_2 to benthic organisms was observed in pH-neutral sediment even at 1,000 mg kg^{-1} (refs. 156–158). Thus, risk assessment must also account for the impact of these passivating transformations on ENM toxicity.

Even this life-cycle perspective on potential risks posed by ENMs does not capture the full picture of environmental implications[159]. The modelling framework of life-cycle assessment (LCA) considers nanomaterials within an entire technological system, so that emissions include not just ENMs but all types of pollutants, and not just those directly emitted but also those emitted upstream (such as from power plants) to produce feedstocks and energy required for ENM synthesis or other life-cycle stages. Using this framework, LCA studies have found that the estimated toxicity impacts of CNT releases are orders of magnitude smaller than the toxicity associated with non-ENM emissions from the production process[160] (Fig. 5). Recognizing the importance of manufacturing impacts, LCA has been used to compare different ENM synthesis routes and identify process changes that will improve environmental performance[161,162].

Because ENMs are usually incorporated into various matrices, risk assessment of a NEP should include not just the ENMs but other product materials as well. In this context, the contribution of ENM synthesis could be a small contributor to overall environmental impacts, with the contribution of ENM releases during product use even smaller[17].

Finally, and perhaps most importantly, a large body of research on the environmental implications of ENMs has focused only on negative consequences and has not considered the environmental benefits that ENM-enabled products confer. Again, using LCA, it is possible to quantify both negative and positive environmental aspects under a unified

framework to determine the net benefits of various nanotechnologies. For example, LCA studies have identified net benefits associated with nano-enabled agrochemicals, chemical sensors, semiconductor components, batteries, medical supplies, food storage and various engineered materials[163–166].

Overall, the amount of ENMs in the environment is negligible in a global context of the nanomaterials cycle, and the potential environmental and health impacts of ENMs are mainly associated with production rather than their incidental release. Thus, ENMs generally pose low environmental and public health risks under most use cases, although accurate risk quantification is challenged by large uncertainty in the data.

Responsible and sustainable use of ENMs

Functional ENMs used in many environmental applications aim to enhance and/or catalyse chemical and biological reactions for pollutant removal, microbial inactivation and sensing. These properties can cause similar unintended and undesired chemical and biological reactions in nature, and possibly in living organisms that ingest them. Thus, safety by design[167,168] is very important to create ENMs and ENM-enabled devices for environmental applications. Considering that public and environmental health risks are a function of both intrinsic hazard (such as ENM toxicity) and exposure, safety by design requires strategies that both minimize the hazard and mitigate the exposure, which are discussed in this section.

Hazard mitigation

Hazard minimization involves prioritizing the use of ENMs that are composed of relatively non-toxic and earth-abundant elements and materials, such as $nTiO_2$ (not withstanding applications that would lead to any notable inhalation exposure such as powders or sprayable products) and food-grade nano-magnetite. Green chemistry can also have a role in mitigating toxicity, not only from the ENMs themselves but also their production as environmentally benign feedstock is normally used. For example, nano zero-valent iron synthesized using neem leaves showed similar performance for hexavalent chromium removal to that synthesized using traditional chemical methods[169,170]. Novel synthesis routes have also been explored using a wide variety of bio-based reducing agents as well as non-hazardous capping agents and solvents[171]. Energy inputs are often an important contributor to costs and emissions from ENM manufacturing[172], so some research has targeted low-energy synthesis techniques using microwaves or ultrasound[173]. Although such approaches can eliminate hazards associated with chemical inputs, they can also have low yields and poor size and shape control. LCA should be used to ensure that these approaches are actually leading to lower life-cycle impacts[162].

Another approach is the three-pillar model: safe product, safe use and safe production[167]. These three pillars are informed at each gate of the stage-gate model and pristine ENMs remain the primary focus. In 2021, a product-oriented approach was proposed, which circumvents the inherent limitations of the linear stage-gate model by considering the NEP life cycle, including production, use, ageing and end-of-life disposal[174,175]. This product-oriented safety by design approach was tested in two cases studies involving the development of two NEPs: a photocatalytic paint amended with $nTiO_2$ for an advanced oxidation process for air pollution control, and quantum dots for biosensing and imaging. Note that lessons learned from these two case studies can be translated for other applications, especially water treatment and reuse, as $nTiO_2$ is frequently considered for photocatalytic treatment[176] and quantum dots have been proposed for sensing waterborne pathogens[70]. These two case studies also contrast the development of NEPs with a short application lifetime (such as cadmium-free quantum dots), for which matrix stability concerns during use are less pressing than for products intended to last multiple years (such as photocatalytic paint). Nevertheless, stability and potential releases after disposal also need to be considered.

The first case study focused on $nTiO_2$-amended photocatalytic paints for air pollution control, in close collaboration with a French paint manufacturer[175]. The initial aim of this case study was to modify existing commercial paint formulations. Initially, the product met the requirements of the three-pillar model, but was eventually proven unsuitable because of decreased performance during ageing and weathering tests, which underscored the importance of interactions between the ENMs and the matrix. Specifically, photocatalytic degradation of the paint matrix resulted in substantial release of harmful volatile organic compounds and accelerated $nTiO_2$ depletion[177]. A product-focused safety by design approach led to a redesign of the paint, by developing a basal mineral matrix that resists photocatalytic degradation without having to modify the active ENM[178].

The second case study[179–182] followed three criteria for designing quantum dots: that they should be less toxic, preserve optical properties and be more stable throughout the product's life cycle. This approach is termed the triple R approach (replacing and reducing the toxic elements and preventing their release). For example, in quantum dot design this can involve replacing cadmium with less toxic elements; reducing the number of toxic elements by doping or combining the quantum dots; and enhancing the capacity of the quantum dot's envelope to prevent the release of toxic ions. Cadmium-free quantum dots were developed with a core composed of InPZn and InPZnS, and with a single, double or triple ZnS envelope. The core of these quantum dots was successfully alloyed with gallium, giving them advanced optical properties. Although the quantum dots exhibit low cytotoxicity, they become toxic after ageing. Comparing their degradation kinetics shows that quantum dots with the thickest outer envelope are, as expected, the most resistant to photodegradation and have the lowest toxic effects throughout the product's life cycle.

Minimizing exposure

Another strategy to enhance safety involves minimizing the amount of ENMs used to minimize the hazard of exposure from incidental release, by selecting ENMs with the appropriate size, aspect ratio, crystallinity, elemental composition and surface properties that enhance functionality and selectivity. Tailoring ENMs to exhibit selectivity towards specific target functionalities would also minimize detrimental side reactions. ENMs can be engineered to preferentially interact with pollutants based on matching properties such as charge, hydrophobicity, surface energy and size. Nanocrystal facet manipulation has also been tested at the bench scale to mitigate toxicity and enhance selectivity to adsorb specific pollutants[88,183,184]. Higher selectivity would minimize the amount of ENMs required for the treatment, and thus potential exposure, as well as potential toxicity associated with unintended side reactions. Note that whereas ENM selectivity might not be sufficient to completely prevent their interaction with vastly complex biological molecules, if released, selective ENMs should lessen unintended effects such as bioaccumulation and toxicity[185,186]. Another common strategy is immobilization (with care to avoid sacrificing ENM functionality) to mitigate their release and enhance their reuse, which enhances cost-effectiveness. For water treatment and reuse, it is particularly important, for public heath purposes, to ensure that no

ENMs or associated metals leach into drinking water during pilot tests under realistic and extreme conditions. Various strategies to immobilize functional ENMs have been explored using different substrates, such as beads, membranes, fibres and porous structures. Immobilization of ENMs can be achieved through physisorption (such as via π–π interactions, hydrogen bonding and electrostatic attraction) or covalent bonding. In practice, different fabrication methods have been developed[187,188]. Mixed-matrix nanocomposites (beads or membranes) embedded with ENMs are readily fabricated by simply mixing the ENMs with the solution of the matrix materials. However, a major challenge is the potential blockage of the active surface of ENMs that reduces activity, resulting in sub-utilization of the ENMs. Therefore, other surface coating methods such core–shell electrospinning, spraying or in situ ENM formation are developed to immobilize ENMs. The immobilization of ENMs enhances their dispersion, which helps maintain their special properties. Sometimes, a synergistic effect between ENMs and substrates leads to improved performance and new reaction pathways[41].

ENMs have also been immobilized onto larger particles that can settle out from a suspension, but ENM release due to fluid shear and particle collision-augmented erosion during suspension mixing is a concern. A packed bed design, where ENM-laden granular substrates are packed to form a porous filter bed[189,190], is an alternative, whereas a largely reduced reactive surface area due to the large size of granular substrates is a fundamental limitation.

Electrodes and membranes are excellent substrates for ENM immobilization. Strategically locating functional ENMs in electrodes or membranes can create synergism with the reaction or separation functions that the substrate provides. For example, ENMs that catalyse oxidative or reductive degradation of a target contaminant can be immobilized on the anode or cathode to enhance the electrochemical oxidation or reduction efficiency[191–193]. In addition, ENMs that selectively adsorb the target contaminants can be immobilized on the electrode to minimize competition by background species (such as NOM), for efficient utilization of oxidants or reductants generated on the electrode surface[194–196]. Compared with the aggressive mixing typically employed to suspend ENM-immobilized substrates, the hydraulic shear on the surface of an electrode is typically much lower, alleviating concerns on ENM loss.

ENMs have been used in membranes to improve both the separation function (such as vertically aligned CNT membranes for desalination[197–199]) and the operation performance of the membrane (such as fouling mitigation by altering membrane surface properties to deter foulant adsorption or attachment[200,201], destructing adsorbed organic foulants[202,203] and inactivating biofilm-forming microorganisms[204–206]), as well as additional treatment functions such as pollutant adsorption or degradation[207,208]. The latter leads to adsorptive and/or reactive membranes that can retain pollutants larger than membrane pores and also adsorb or destroy small pollutants that could penetrate the membrane. ENMs with specific surface properties (such as charge and surface functionality) have been explored to allow membranes to selectively reject or permeate[209] target solutes in applications such as resource recovery during desalination[15,195,210]. However, ENMs applied as a coating can reduce membrane permeability; thus, some membranes have been made using ENMs as building blocks[211] (such as graphene[62,212] and covalent organic framework[213,214] membranes). ENM-loaded membranes have seen some commercial success since the 2000s, including air purifier and ceramic membrane filters.

In addition to embedment, ENM release due to detachment or dissolution can be minimized by reducing the ENM size, so that the fraction of atoms involved in surface anchoring (via covalent bonding or chelation) is increased. Consequently, anchoring very small sub-nanometre ENMs or individual atoms instead of large clusters represents the endeavour towards controlling materials at the smallest possible scale. Atomically dispersed catalysts, often termed single-atom catalysts, exhibit properties between metal clusters (heterogeneous catalysts) and organometallic complexes (homogeneous catalysts) with respect to their coordination environment. They often exhibit uniquely enhanced or selective catalytic performance that can be instrumental in water treatment scenarios involving a complex matrix[215,216]. They are particularly appealing to water treatment application of rare-earth elements (such as platinum-group catalysts for nitrate reduction) due to near 100% atomic efficiency, markedly reduced material cost, synthesis simplicity often comparable with ENMs and likely fewer environmental concerns. However, the environmental application of single-atom catalysts is currently at the embryonic phase at most.

ENM immobilization decreases its consumption (by enabling reuse) and can mitigate the potential release, thus mitigating potential risks. However, although large quantities of research have been devoted to synthesizing advanced nanocomposites with superior adsorption, separation and catalytic performance for water treatment applications[217], the long-term stability and potential release of immobilized ENMs are seldom evaluated[218]. Only a few studies have demonstrated the mitigated or controlled release of metal ions from metal or metal oxide ENMs, which was successfully applied in commercial products. For example, loading metal (such as silver or copper) or metal oxide (such as nZnO) ENMs onto beads such as nanozeolite[206,219], SiO_2 (ref. 220) or CNT support substantially decreased the release of the corresponding metal ions (and thus prolonged the usage lifetime), while maintaining or even enhancing antibacterial performance[188].

Note that ENM release is strongly dependent on the properties of ENMs and substrates, the immobilization method and the application scenario. Generally, ENMs immobilized by chemical bonding (for example, Ag–S bond[220]) have stronger anchoring and are less prone to release. In situ ENM formation leads to less ENM release compared with spraying or simple adhesion, as shown for palladium and indium nanocatalysts on hollow fibres[138]. Still, the quantity of release varies between different in situ ENM formation methods[138]. Currently, no standard protocols exist to evaluate ENM release under different scenarios, which impedes comparisons of the effectiveness of different ENM immobilization strategies.

As discussed in previous sections, given that the greatest health risk of ENMs is often associated with inhalation during manufacturing, it is important to promote a culture of safety in manufacturing by iterating with the Occupational Safety and Health Administration on best practices. It is also important that ENM-enabled treatment devices and processes undergo independent certification (such as by the National Sanitation Foundation International) for meeting performance and safety standards, which is an important aspect of technology legitimization and social acceptability. Several safety by design approaches have been used for ENM development, inspired by the pharmaceutical industry. The traditional approach is the linear stage-gate model[221] that breaks down the development of a new product into a series of phases (such as ideation, development, piloting and scale-up); for example, from low to high Technology Readiness Levels, separated by gates that are crossed when the requirements of the preceding stage are met[221]. For instance, at each gate a decision is made to proceed with or without minor modifications, repeat the stage

with major modifications, wait for other technologies or regulations to develop, or terminate[222]. Decisions must balance expected risks, costs and benefits. In this stage-gate model, pristine ENMs are the primary focus throughout the entire development process.

Social considerations

Social acceptance is an important consideration for widespread and sustainable use of ENMs in environmental applications. Working towards social acceptance requires recognizing and addressing social barriers to the adoption of novel nanotechnologies, which typically involve cost, fear, perceived usefulness and implementation complexity (including regulations). For many environmental applications such as water treatment and reuse applications, cost (relative to more conventional technologies) is often the most important adoption barrier. Strategies to reduce ENM cost include immobilization to facilitate recyclability, using low additive ratios to impart the desired properties, avoiding diminishing returns of ultra-high purity[223] that is customarily needed for research and taking advantage of the economy of scale as the demand for NEPs increases. To address fear and implementation complexity concerns, it is important to engage multiple stakeholders via surveys and interviews early in the innovation process, to minimize misconception-related adoption barriers (such as exaggerated toxicity fears). Such engagement is also critical to enhance technology legitimization[224], which is the "generalized perception or assumption that a technology is desirable or appropriate within its social context"[224]. Based on structured interviews in North West Europe, the main factors influencing societal acceptance of nanotechnology applications were reported to be the extent to which ENM applications are perceived to be beneficial, useful and necessary, and how physically close to the end user these applications are perceived to be[225]. Another public survey found that potential social acceptance generally increases with knowledge of the ENM properties and the enabled functionalities[226], underscoring the importance of public education and outreach. Regarding the industrial perspective, a survey on businesses involved in water treatment found little substance about anecdotal concerns to develop and market NEPs because of perceived onerous regulation. The main concerns were actually cost and public perceptions affecting the long-term viability of NEPs for drinking water purification. To alleviate this latter concern, providers of water treatment equipment or services favoured government regulation of ENMs to alleviate concerns about public safety, and independent certification of the NEP used for water treatment.

To ensure responsible and sustainable application of ENMs, several strategies should be considered during their design production, including safety by design, effective immobilization and green chemistry manufacturing. Additionally, ENM-enabled products and processes should undergo a certification process to meet the safety standard and increase social acceptance. Early engagement of stakeholders is also important.

Summary and future perspectives

This Review highlights that ENMs are promising for environmental applications, yet their practical application is still hindered by barriers associated with large-scale manufacturing and cost-effectiveness. Although concerns regarding the potential health and environmental impacts of ENMs have been raised, we summarize that as ENMs occur at low concentrations and undergo different passivation processes in aquatic and terrestrial environments, they generally pose a low risk over their life cycle. Further, by adopting sustainable nanomaterial manufacturing and immobilization strategies, the release of ENMs into treated water and the environment can be minimized further. A notable exception is the potential high risk associated with occupational exposure to ENMs via inhalation during some manufacturing activities, which is beyond the scope of this Review.

Advances in nanotechnology to address challenges at the water–energy–food–climate nexus could be realized by molecular, bottom-up design approaches for the fabrication of novel structures with angstrom-level precision. Such material architectures, designed at the molecular or atomic level, could overcome the limitations of existing approaches that utilize nanoscale building blocks, which often result in inferior performance compared with conventional technologies. For example, using carbon-based nanomaterials (such as 2D GO nanosheets) as building blocks to fabricate desalination and water purification membranes has proven to be very difficult due to inherent defects, resulting in membranes with lower performance than state-of-the-art polymeric membranes[227]. Similarly, the use of CNTs and graphene-based materials as building blocks for adsorbent materials often results in lower solute removal than mature, low-cost technologies, such as activated carbon[227]. Molecular-level design of materials with uniform sub-nanometre channels and chemical functionality tuned at the angstrom level, for example through self-assembly of small molecules, could overcome these limitations[227]. However, to achieve this goal, there is a crucial need to develop molecular-level design methods and fabrication techniques for scaling up these molecular-level designs to large functional engineered materials and systems. This effort will require interdisciplinary research involving the fields of chemistry, molecular engineering and materials science.

Progress in the environmental application of nanomaterials will be further enhanced by molecular simulations, computational chemistry, process modelling and techno-economic analysis (TEA). Molecular simulations and computational chemistry will inform the design of molecular architectures and nanoscale systems with precise control of the size, microstructure and chemical functionality. Such computational tools are also essential for understanding the mechanisms and performance of the nanostructures, which, in turn, can further optimize the design and fabrication of the nano-based devices. Process modelling is needed for designing the most efficient system and for estimating the energy consumption of the technology[228]. Process modelling also provides valuable input to TEA for assessing the viability of the proposed nanotechnology. TEA, which is often overlooked in the field of environmental nanotechnology and materials science, should be a required component in the overall design and development of advanced environmental nanotechnologies[228]. Such analyses can assess the viability of proposed advanced technologies compared with conventional technologies. For example, TEA and process modelling have shown that direct seawater electrolysis with novel catalysts is not useful or viable, as desalination and purification of the seawater prior to water electrolysis will incur less than 0.5% of the total cost of the process[229,230]. Importantly, TEA can also project the future status of the proposed technology upon further advances in materials and fabrication techniques.

In addition to the importance of anticipatory TEA, future research focus also includes enhancing the selectivity of ENMs to minimize ENM mass requirements and mitigate side reactions and release (thus contributing to safer applications). Considering the growing needs for modular, distributed and electrified technologies, both electrocatalysis and membrane processes present excellent opportunities to explore ENM environmental applications.

There is also a need to engage multiple stakeholders early in the innovation process to minimize misconception-related adoption

barriers (for example, legitimization of novel technologies). Additionally, it is favoured to have government regulations on ENMs and ENM-enabled products and processes, and implementing a certification process for these products is necessary to meet the safety standard and increase social acceptance. The precautionary principle must be balanced with accelerating innovation, so public health can be protected without excessive caution that delays potential benefits to society.

Overall, nanotechnology has benefited from an integrated multidisciplinary approach to advance understanding of the fundamentals of nanoscale phenomena in environmental and engineered systems, and the safety and reliability of specific nanotechnology-enabled products and processes. Continuing a use-inspired basic research strategy starting from solving practical problems[231], and multidisciplinary convergence involving the integration of knowledges from multiple disciplines, will help protect and even enhance environmental and human health, while ensuring the long-term sustainability of the nanotechnology industry.

Published online: 23 July 2024

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Acknowledgements
The authors thank the Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment (NEWT) and the Rice University Water Technologies Entrepreneurship and Research (WaTER) Institute for support.

Author contributions
The authors contributed equally to all aspects of the article.

Competing interests
The authors declare no competing interests.

Additional information
Peer review information *Nature Reviews Earth & Environment* thanks H. Yu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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