Paradigms to Assess the Environmental Impact of Manufactured Nanomaterials


Visualize printing all 24 volumes of the Encyclopaedia Britannica on the head of a pin. In 1959, Richard Feynman articulated this reality in an insightful address at the annual meeting of the American Physical Society. In what became a prophetic speech, “There’s plenty of room at the bottom” [1], Feynman discussed manipulating and controlling matter on a small scale. Back then, forward thinking conjured images of going to the moon in an era when computers occupied entire floors of buildings. Fifty years later, we no longer have to imagine. We are actively manipulating and controlling materials and devices on the scale of nanometers.

With these advances, researchers have heralded both positive and negative effects of nanotechnology. Advocates point to efficient energy consumption, a cleaner environment, and eradicating health problems. Others have noted we do not know enough about how nanomaterials function, how they add potential stressors to the environment, or what chemical reactions may result when nanomaterials meet other particles. Both groups have called for further debate and advanced research into nanotechnology to determine the balance between risks and benefits.

The ability to build products inexpensively with almost every atom in the right place holds tremendous promise for advances in virtually every sector of society. For example, smart drugs will deliver medicine only to the cells that need it; strong yet light materials will be used for automobile bumpers, airplanes, and tennis racquets; and tiny reactive particles will clean water at a fraction of previous costs. Although these benefits are exciting to scientists, they are often mysterious to the general public. One unknown involves the safety of these emerging materials, often called engineered nanomaterials. Scientists characterizing the environmental, health, and safety of nanomaterials (Nano EHS) are obligated to produce reliable data on which quantitative risk assessments can be built. In the past two decades, scientists have advanced this area, learned from mistakes, and realized that tools developed for working with substances dissolved in a solution cannot a priori be applied to particles. Although life on earth evolved in the presence of natural nanomaterials (including carbon, cellulose, and nanosilver), engineered nanomaterials—those produced for a specific purpose—may be identical to natural nanomaterials, but pose potential hazards due to significantly elevated environmental concentrations. In many instances, the question may be how engineered nanomaterials differ from natural nanomaterials. It is precisely this difference that may define their potential for adverse effects.

Against this background, this article seeks to answer several questions: Where does the science need to provide reliable data that will assist policymakers and regulators develop strategies to manage nanomaterials and instill public

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confidence regarding the safety of these materials? What are the critical needs that will move us forward safely and intelligently in this promising field? Are the paradigms generally developed to assess the fate and effects of solute contaminants applicable to nanomaterials? We propose a way to answer these questions and move Nano EHS forward, creating a new framework for detecting, determining the fate, characterizing the hazards, and assessing the risk of engineered nanomaterials. To understand why and how these frameworks are relevant, we must first look at what nanotechnology is, examine the current state of the field, and highlight the issues inherent in studying nanotechnology.

What Is Nanotechnology?

Nanotechnology is the science of manipulating materials on the atomic and molecular level. While Eric Drexler is credited with coining the term nanotechnology in the 1980s [2], Feynman is credited with heralding its coming. In the years since Feynman’s speech, focused research and development funding from governments and companies worldwide has

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<td>Use of nanomaterials in water filtration and purification.</td>
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impelled the rapidly expanding nanotechnology markets, which now include more than 1,000 commercially available products. These products either contain nanomaterials or have been produced using nanotechnology (http://www.nanotechproject.org/inventories/; see Nanomaterials Among Us: Their Risks and Benefits). The scientific community is now routinely asked to engage the public during research, which has led to the notion that nanotechnology must be innovated responsibly. This concept has become global as governmental agencies push this agenda (see, for example, http://tinyurl.com/cttu8jy). The potential applications for nanomaterials are growing exponentially, with products and processes rapidly moving out of the research laboratory and into commercial operations. Compared with traditional chemicals, risks associated with nanomaterials are largely unknown. Yet, engineered nanomaterials are being used every day in many sectors of our society and undoubtedly enter the environment.

How Small Is Small? And Why Does It Matter?

Nanomaterials, the physical structures that make nanotechnology possible, include all materials that contain nanoscale structures. The nanoscale is 1 to 100 nm—one billionth of a meter. At this size, the characteristics of materials change: their strength, conductivity, and reactivity differ substantially from macro- or micron-sized materials, shifting the ordinary rules of physics and chemistry to the sidelines. Although it is difficult to imagine something one cannot actually see, nanomaterials are the smallest increments of the physical world and are at a similar scale to the biomolecules key to crucial life functions. The typical distance between two carbon atoms in a molecule is 0.12 to 0.15 nm; the diameter of a DNA double helix is about 2 nm; the diameter of Buckminster fullerene, also known as C_{60}, is about 5 nm. The similarity in size between these natural biomolecules and manufactured nanomaterials translates into an increased potential for manufactured materials to interfere with biological processes. This could include the behavior of cell membranes, biochemical pathways in cells, or even the genetic code itself.

Let us put nanoscale dimensions into perspective. Imagine shrinking the moon to the size of a tennis ball. This is the same as shrinking the tennis ball to the size of a Buckminster fullerene molecule (Fig. 1). As materials are “nano-sized,” physical phenomena change from those of the bulk materials (adding as little as 2% by volume of silicate [common clay mineral] nanoparticles to a polyimide resin increases its strength by 100%). These phenomena do not appear as macro materials are reduced to microns, but begin to show up when they shrink to the nanometer range. In nanometers, the surface-to-volume ratios become huge (see Particle Size Versus Surface Area). As a result, unexpected mechanical properties may emerge, and catalytic activity may become apparent. For example, carbon nanotubes are elongated structures composed entirely of carbon that behave in a completely different way than do traditional pure carbon materials such as graphite. Carbon nanotubes have extraordinary tensile strength, with carbon nanotube fibers spun from individual nanotubes being strong yet lightweight enough to be used in bulletproof materials. New generation carbon nanotube fibers have a strength-to-weight ratio about 117 times that of steel [3], making them one of the strongest materials known to humankind.

We Need Better Information

The unique characteristics of nanomaterials bring a new dimension to environmental effects testing. The physical and chemical properties that make nanomaterials unique also equip them with the potential to affect humans and the environment adversely. The physical form of the material matters, which is equally as important as its chemical reactivity. Indeed, the structure and reactivity of nanomaterials are linked inextricably. For example, mechanistic logic on reactive oxygen chemistry would suggest that modifying the surface of a nanomaterial to make it photoreactive to facilitate the oxidation of microorganisms might also increase the potential for oxidative injury to organisms (such as TiO_{2} nanoparticles in fish [4]). Despite existing laboratory research that helps us understand nanomaterial fate, our ability to estimate exposure concentrations is poor, which results in
high levels of uncertainty in estimating risk. Without trustworthy information from scientific or regulatory sources, the public may be more likely to believe the emerging alarmist literature on nanomaterial hazards (http://www.foe.org/pdf/ Nano_Sunscreens.pdf).

The two components of risk, hazard and exposure, seek to identify the innate harm a particular substance may present and the potential for an organism to encounter that material. In traditional scientific inquiry, assessing risk requires linking physical and chemical behavior to effects on the human body, other organisms, and the environment. Our inability to develop quantitative risk assessments for nanomaterials with acceptable levels of uncertainty stems from the uncertainty inherent in our current estimates of exposure and toxicity. Furthermore, few toxicity studies have quantified chronic effects or the consequences of bioaccumulation.

Unfortunately, assessing the hazard associated with nanomaterial exposure and characterizing risks have not kept pace with nanotechnology advances. One reason for this gap is that research generally requires limited physical and chemical characterization, and perhaps only modest effort on toxicological assessment to answer the immediate research question related to the innovation. Regulatory bodies, in comparison, often need large and robust datasets. Specifically, a primary driver of this information gap is funding. According to the National Nanotechnology Initiative (www.nano.gov), between 2005 and 2011, almost $10 billion will have been spent in the United States on nanotechnology research. During that same period, only $480 million (less than 5%) will be spent to understand the environmental, health, and safety issues related to developed nanotechnologies. In addition, new materials that are not used as pesticides or food additives fall under the regulatory purview of the Toxic Substances Control Act. This act does not require a robust toxicological dataset for materials registration. Hence, emerging materials such as these are being used within society with a minimal hazard characterization. This lack of investment and lack of regulatory incentive has resulted in both humans and ecosystems being exposed to nanomaterials without an accurate picture of the probability that the nanomaterial used may cause harm.

In the last few years, the urgency to understand these effects has produced a growing body of research on human and environmental hazard and exposure [6–8]. While research studies to characterize the risk of nanomaterials to humans have generally focused on occupational exposure and inhalation toxicology, risk to the ecosystem presents a more diverse challenge: to engage physicists and material scientists in understanding particle structure, environmental engineers to quantify particle release, chemists to understand behavior, and biologists and toxicologists to quantify bioavailability and toxicity in different trophic levels. Ultimately, quantifying ecological risk will also complement assessing the effort to quantify human risk. The very real possibility exists that nanomaterials may move through foodwebs and culminate in human exposure [9].

The infancy of this research and the unique physical and chemical characteristics of nanomaterials compound the challenge regulators and industry face in understanding and managing potential risk from nanomaterials. Although some may believe human health is more important than environmental effects, the intimate link between the two and the intrinsic protection value of ecosystems and their functions call for including both in assessing risk. To that end, ecotoxicologists have used standardized testing methodology and standard test organisms in the rush to understand the effects of nanomaterial exposure. The result? Ecotoxicologists overwhelmingly treat nanomaterials in the same way they have considered traditional chemicals for more than 40 years. They use the same bioassays and endpoints and assume that nanomaterials behave the same as soluble contaminants. Quantifying the behavior and effect of nanomaterials in organisms and environmental media, however, has proven to be more difficult than previously experienced with soluble chemicals. Many of those methods are proving inadequate and do not adapt well to the unique properties of nanomaterials. The scale of the task to completely characterize hundreds of materials through dozens of methods is as vast and growing as rapidly as the number and types of nanomaterials increase. Moreover, the diffuse disciplinary areas and the rapid pace of nanomaterial risk research create challenges in providing a clear snapshot of the current state of science and paths for revising methodologies.

In a nutshell, here is the problem: assessing the risks of nanotech advancements is way behind developing those advancements. This gap exists for three reasons. First, the scientific research required to develop nanotechnology does not yield adequate data to assess the risks of those products. Second, scientific research data are not adequate for risk assessments because the regulatory agencies require much more robust data sets (50 endpoints vs 2 lab-model endpoints). Third and finally, research on the environmental health and safety of nanomaterials receives less than 5% of the funding spent to develop new nanomaterials.

So, this raises the question: What can we do?

Understanding the Environmental Impact of Nanomaterials

We can start to address the above situation by understanding the environmental effects of nanomaterials, which requires detailed knowledge of both the fate and behavior of the materials in the environment and biological effects (hazards). Critically, it is vital to understand the interplay between environmental chemistry and ecotoxicology so that effects on the ecosystem can be understood or predicted. We must
not lose sight of the overall goal of sustaining biodiversity and ecosystem functions while allowing for innovations in nanotechnology. During the past decade, nanomaterial fate and transport have become a major focus of research. Several review papers have highlighted the way environmental factors such as calcium concentration, pH, and the effects of organic ligands will alter the colloid behavior of nanomaterials and influence their ultimate fate [6–10].

The scientific community is on a steep learning curve, however, but has the benefit of hindsight. Much of the peer-reviewed literature published in the early 2000s lacked adequate experimental controls or appropriate methodology simply because it was not clear what facets of experimental design would be the most important for studying nanomaterials. Nanomaterial characterization—describing the physical and chemical characteristics that drive and affect particle behavior—has been inadequate or incomplete. Quantitative exposure metrics that describe precisely how experiments were performed to isolate the causal effects were insufficient. More recent publications have attempted to overcome these inadequacies. While progress in this area is evident, research in this field is hampered by little experience with particles as contaminants. For example, until now, ecotoxicologists

A key characteristic surrounding the concern of nanomaterials with respect to ecological and human health is the extremely high surface area to volume ratio. This illustration and table depict changes in the physical characteristics of gold particles at a constant mass of 1 μg as they are subdivided to approach, and reach, the nanoscale: (A) 1 particle, (B) 10 particles, (C) 100 particles, and (D) 1,000 particles all of which have a combined mass of 1 μg. At a constant mass, there is a three-order-of-magnitude change in particle diameter for this conceptual model to reach a nanomaterial. More important, however, is that the total number of particles that represent this decrease in particle diameter increase nine orders of magnitude. As a result, total surface area of the depicted mass of particles increases three orders of magnitude. Concern about this phenomenon emanates from the fact that while the same amount of elemental material may enter a given system, contaminants on the nanoscale are greater in number, may be translocated to more and different locations, and have the potential to deliver a higher exposure of complex material attached to their surface.
Collaboration Is Key

Clearing this hurdle is not simply a matter of understanding and solving the new scientific problems that engineered nanomaterials pose. The infrastructure for environmental science also needs to be adapted. Clearly nanoscience is a worldwide concern and interdisciplinary collaboration. Several countries have national initiatives investing in nanotechnology environmental health and safety. These include the National Nanotechnology Initiative and the European Union’s Seventh Framework Programme on nanotechnology (http://cordis.europa.eu/ftp7/home_en.html). Both of these efforts are multidisciplinary. In the United States, the National Nanotechnology Initiative is coordinated by the White House and involves 25 federal agencies. Although more than 60 nations have similar initiatives, coordination is needed worldwide to invest limited resources and make the best use of the data generated by subsequent research. Many nations are cooperating to build scientific understanding and develop these materials responsibly through international forums such as the Organisation for Economic Co-operation and Development and the International Organization for Standardization. These international activities are focused on developing common global standards, definitions, and test methods, and on providing a better understanding of the physical and chemical properties of nanomaterials that could affect human health or the environment.

At the institutional level, it is no longer sufficient for toxicologists to work with chemists and biochemists to explore toxicant bioavailability and modes of action. Rather, to understand the impacts of nanomaterials this team must include, among others, material scientists who understand the synthesis, structure, and innate properties of each material; physicists who characterize nanomaterial behavior; and specialist areas of life sciences to understand how information regarding exposure and effects can be incorporated into ecological risk assessment, and concerns about the inability to tie adverse effects causally to specific nanomaterial properties will result in the need to test each of the exponentially increasing number of nanomaterials. Even under the most optimistic assumptions, the cost and time to evaluate the risk associated with just nanomaterials currently being used is huge (see discussion in Choi et al. [11]).

Moving Nano research Forward

With increased collaborative efforts, creative scientists can still find paths forward. To reach the ultimate goal of developing quantitative risk assessments that regulators can use with a high degree of confidence, several areas of Nano EHS must be addressed. The current paradigm for characterizing the fate and effects of contaminants should be reconsidered and modified to accommodate the unique challenges of nanomaterials. Challenges facing Nano EHS research including detecting these materials in biological and environmental matrices; predicting the environmental fate of nanomaterials; assessing the hazard of these materials; and ultimately developing quantitative risk assessments (Table 1).

Detecting nanomaterials

Today, analytical chemistry is equipped well to detect environmentally relevant concentrations of traditional pollutants such as trace metals, pesticides, or persistent organic pollutants. For some of the hydrophobic organic pollutants, their environmental concentrations are typically far below aqueous solubility, and chemists have developed complex methods to extract such persistent organic chemicals. These challenges, however, have also shifted the focus from the water to matrices where the organic chemicals accumulate such as soil or the tissues of organisms. This has provided environmental chemists with tools to explore the fate and behavior of considered only soluble forms to be bioavailable, whereas insoluble forms were considered nonbioavailable and therefore nontoxic. The lack of standardized approaches to characterize the ecological effects of particles, uncertainty regarding how information regarding exposure and effects can be incorporated into ecological risk assessment, and concerns about the inability to tie adverse effects causally to specific nanomaterial properties will result in the need to test each of the exponentially increasing number of nanomaterials. Even under the most optimistic assumptions, the cost and time to evaluate the risk associated with just nanomaterials currently being used is huge (see discussion in Choi et al. [11]).
poorly soluble chemicals in the environment. That some of these approaches could also be adapted to work with nanomaterials remains feasible.

To detect and characterize nanomaterials, however, several challenges have emerged from the solid-state properties of nanomaterials. First, the chemical speciation concept used widely in the analytical chemistry of traditional soluble pollutants needs to be expanded to include physical forms. This will enable analytical chemists to optimize techniques for forms that are most meaningful in the context of assessing the risk assessment of nanomaterials. Recently, many techniques have been borrowed from colloid science. These techniques, however, are well established for pure systems, but not yet for nanomaterials in complex environmental systems. Complex environments, whether natural or laboratory assays, bring specific challenges. These challenges include the fact that natural environments are not at equilibrium; the redox potential of a natural environment is difficult to mimic in a laboratory bioassay; and nanomaterial aggregation state changes continuously during bioassays [14]. Differentiating engineered nanomaterials from backgrounds of similar but natural materials is also difficult. Furthermore, uncertainties in analytical detection often require using multiple, independent methods to confirm detection [15]. Another challenge includes achieving sufficiently low detection limits (ppb or sub-ppb levels) to realistically monitor nanomaterials in environmental compartments. It should be noted, however, that assessing effect concentrations may be sufficient at parts per million and sub-parts per million. Finally, the problem of altered nanomaterials (aging or weathering) during their environmental life cycle is a challenge. Multiply these challenges by the number of nanomaterials, (altered) nanomaterial forms, and possible environmental matrices and conditions, and the research effort to develop adequate analytical chemistry becomes daunting. Consequently, the input of toxicologists is crucial to apply analytical efforts to the relevant questions. For example, one challenging question is this: Which nanomaterial property (concentration? surface area? particle number?) should be chosen as an endpoint in nanomaterial effect studies?

Predicting Fate
Expecting that nanomaterials will behave differently than soluble chemicals in the environment is reasonable. Although molecular transport is almost entirely via water or adsorbed to a particulate, particle transport needs to account for agglomeration and aggregation processes and consider both aerial as well as hydrological movement. As with most contaminants
in the environment, nanomaterials can be expected to end up in aquatic ecosystems or soil, either from direct release, release from products, or as a material contained within products. The fate of each of these nanomaterials will vary. The released and subsequently aged and transformed nanomaterials are most relevant to ecotoxicology; yet, a commonality among the research on environmental risks of nanomaterials is the use of pristine nanomaterials. Today, however, awareness is growing that nanomaterials released from a matrix are often still embedded in the matrix; therefore, the environmental behavior of the nanomaterial is still determined to a large extent by the properties of the matrix. Differences between pristine nanomaterials and those actually released or altered after release are highly significant for fate processes in the environment, but information on this issue is lacking.

More specifically, we have insufficient knowledge on the nature of nanomaterials that are actually released, the fate and effects of altered and aged nanomaterials, product-specific nanomaterial fate processes, and product-specific time scales for nanomaterial alteration or transport processes. These issues reflect in part the scarce knowledge we have on the identity of nanomaterials industries use and incorporate into their products. Consequently, further research needs to show if the aging and transformation processes result in a similar or more diverse set of nanomaterials. For example, does coating a surface with a naturally occurring material override the initial coating of the material? Thus, do nanomaterials with different coatings behave similarly after being aged and transformed in the environment? Another key question is whether nanoparticle–product combinations might require a specific risk assessment because of the aforementioned differences? Answering these questions is now most relevant because it is not the pristine, but the altered and probably the product-specific nanomaterials that are actually present in the environment.

Assessing Hazard

Once in the water, nanomaterial behavior will dictate not only transport, but also which organisms are most likely to encounter them. The decision to conduct specific ecotoxicity tests should be predicated on understanding nanomaterial behavior in the aquatic ecosystem. Unfortunately, applying current testing methods developed for water-soluble materials to characterize the hazard associated with nanomaterials has been inadequate [15]. The literature includes many examples where standard bioassays with pelagic organisms have been used to characterize the hazard associated with a particular nanomaterial despite the fact that the vast majority of the particles sediment out of the water column within a few
hours of test initiation. Numerous other inadequacies emerge in applying current toxicity testing methods to evaluate nanomaterials. These include nanomaterial measurement and characterization, running appropriate controls, and assessing the appropriate endpoints. For example, several investigators have concluded that the toxicity of carbon nanotubes was not due to some biochemical interaction; rather, the toxicity was due to clogging the intestinal tract and interfering with food processing and assimilation [16]. The evolution of ecotoxicity testing methods can be viewed as a refinement in the current toolbox of methods.

As assessing the hazards of nanomaterials moves forward, considering recent approaches that incorporate rapid screening and in vitro testing whose results prioritize whole animal testing is important [17]. These approaches produce large amounts of “omics” and high throughput screening data and rely on computational toxicology to evolve hypotheses of toxicological mechanisms from these datasets. The relationship between results of both in vitro and high throughput screening efforts and whole animal testing must be characterized. Without this characterization, these efforts may waste valuable resources while providing minimal contributions to assessing the hazard of nanomaterials.

**Developing Risk Assessments**

Quantifying nanomaterial exposure and effects are challenges facing environmental scientists. Risk assessment is defined as quantitatively determining the probability that a contaminant will cause harm given particular use scenarios. This is where the rubber meets the road in ultimately translating science into societal action. Assessing risk provides managers with the distillate of science that they integrate with socioeconomic and political information to produce policies to manage human activities and produce and use products. The challenge here to environmental scientists is, can we use current risk assessment paradigms to quantify the risk of nanomaterials?

Our profound lack of knowledge in the environmental fate and transportation of these materials, the ability to detect these materials, and the understanding of how specific exposures affect human health and ecological resources limit risk assessments and result in high levels of uncertainty (Fig. 3). Of these data gaps, the largest source of uncertainty for nanomaterials stems from the way in which nanomaterials behave in environmental media and how we quantify the actual exposure these organisms experience via bioavailable nanomaterials. Data needs for risk assessment of nanomaterials may deviate from those of traditional chemicals; these data need to include information on physics and physical form as well as nanomaterial aging and alteration. Consequently, risk assessment will be helped considerably by improving the characterization of physical form, methods of detecting and testing, and describing the transport processes. Despite these constraints, risk assessment is currently possible, though reducing uncertainty in exposure

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**FIGURE 3:** Propagating uncertainty in risk assessment. Qualitative illustration of how uncertainty in the effects and exposure data can result in unacceptable uncertainty in characterizing risk. In most instances, uncertainty in solute risk assessments comes from dataset weaknesses or lack of information, but not from quantitative measurements of the contaminant. Nanomaterial risk assessments face significant uncertainty in particle characterization and quantification in addition to the uncertainty in solute risk assessments.
and effect assessment remains a challenge. Forensic assessments of nanomaterials will remain difficult until analytical techniques are sufficiently developed to detect nanomaterials in complex environmental media [15]. Rapid improvements in our ability to detect and characterize nanomaterials and put their behavior and effects in both bioassays and natural systems will substantively improve the robustness of risk assessments. Improving risk assessments with reduced uncertainty will enable risk managers to make more informed decisions about managing nanomaterials.

Implications for Risk Management

A consensus view exists that the paucity of usable data on the environmental hazard of nanomaterials has created unacceptable uncertainty in risk analysis from the regulatory decision-making perspective. This lack of information—despite so many products being produced and used in society that contain nanomaterials—places regulators in a precarious position. If we err on the side of overregulation (using the precautionary principle), economic growth may be suppressed. This might unnecessarily lead to less research and development and delay or eliminate the potential societal benefits of nanotechnology. Erring on the side of under-regulation (safe until proven hazardous) may lead to significant ecological or health catastrophes such as occurred with DDT, mercury, asbestos, or thalidomide.

The ultimate goal of assessing risk is managing risk. If one considers the benefits of nanomaterials and assumes they are projected with the same degree of rigor that went into assessing risks, then society can make informed decisions regarding the use of nanomaterials. The implications of this for government regulators and industry are significant. As the entities responsible for funding risk assessment and controlling risk, government and industry are on the front lines of solving these challenges. Many have recognized the high level of risk uncertainty due to limited data and the profound limitations of analytical methods. The critical reviews included in this special issue provide finer detail on those specific challenges. Multiple efforts to augment regulatory decision making in the face of this uncertainty have provided adequate risk management methodology for the near term, including using existing chemical risk assessment paradigms, validating these factors for nanomaterials, forgoing nanospecific uncertainty factors given our current risk understanding, using interim risk assessment recommendations, and establishing tentative exposure limits based on extrapolated data from recent studies. Still, fully implementing these methods remains problematic with regard to exposure assessment.

The current limitations of our understanding are coupled with additional challenges. Third- and fourth-generation nanomaterials such as nanodevices with increasingly complex bioreactive and self-assembling capabilities pose additional and largely unknown challenges compared with current nanomaterials. Although the scope of this analysis is confined to environmental assessment, the implications for human health exposure and risk should not be ignored.

Although government and private firms have invested heavily in recent years in nanomaterial risk assessment, the looming body of uncompleted work and the limited available funding for such work call for an immediate and coordinated global effort to prioritize and address the most significant likely risks. Multiple efforts to identify minimum physical and chemical characterization needs have yielded consistent recommendations. No such effort to extend this thinking to toxicological testing exists despite the fact that toxicology requires significant time, money, and manpower. Developing minimum toxicology recommendations would aid prioritization efforts. Moreover, the lack of strategically coordinated funding limits the impact of current research funds.

To move the field of Nano EHS forward, it is critical to realize that the paradigm of considering only soluble contaminants as toxicologically relevant is obsolete. In addition to incorporating particles into our conceptualization of potential contaminants, the concept of particle aging and transformation must be considered. To appreciate the breadth of the challenge of Nano EHS research fully, the paradigm of interdisciplinary environmental research must be expanded to include physical scientists with knowledge of these emerging materials. Meeting the challenges of Nano EHS will require new multidisciplinary research teams that can evolve new approaches that take into consideration the particular physical and chemical properties of these emerging materials.

Acknowledgement

An international gathering of 28 scientists in Clemson, South Carolina, USA, in August 2010 discussed nanomaterials in the environment under the auspices of a technical workshop sponsored by the Environmental Protection Agency, Arcadis-US, and the Clemson University Institute of Environmental Toxicology and endorsed by the Society of Environmental Toxicology and Chemistry. Their work provided the impetus for this article, and the results are contained in this issue’s three critical reviews authored by Handy et al. [14], von der Kammer et al. [15], and Nowack et al. [18].
### Coming to terms...

**Agglomeration**—A loose arrangement of parent particles loosely attached. This attachment can be undone easily. Aggregates can form agglomerates.

**Aggregation**—Irreversible attachment of parent particles (under normal conditions). The inner surface area is inaccessible, so the outer surface area is less than the total of parent particle surface areas.

**Biological nanomaterials**—Materials that make up biological molecules (proteins, carbohydrates, nucleic acids, lipids, hormones, and so forth) manufactured in a specific design for a specific technology in the nanoscale.

**Buckminster fullerene**—Specifically refers to the allotrope of carbon consisting of 60 atoms arranged in 12 pentagonal and 20 hexagonal faces to form a hollow sphere, commonly referred to as C60. The Buckminster fullerene is named after Richard Buckminster Fuller, the inventor of the geodesic dome, which is similar in design to a C60.

**Carbon nanomaterials**—Naturally occurring or manufactured nanostructures of carbon including fullerenes, tubes, fibers, needles, and cones.

**Carbon nanotubes**—Allotropes of carbon that are graphene sheets rolled into a cylindrical shape (single-walled nanotubes) or multiple tubes of increasing diameter (multiwalled nanotubes). Carbon nanotubes have a large length-to-diameter ratio and exhibit extraordinary strength and unique electrical properties, making them attractive for many materials applications.

**Colloid**—A homogeneous, noncrystalline substance that is dispersed throughout another substance. A colloidal system consists of two phases: the dispersed phase (the colloid) and the continuous phase (the media in which the colloid is dispersed). A colloidal system may be solid, liquid, or gaseous. Colloids may range in size from 1 to 1,000 nm.

**Dispersion**—A distribution of particles within media.

**Engineered nanomaterials**—Particles with at least one dimension that is less than 100 nm that have been manufactured and not created through environmental processes.

**Fullerenes**—Allotropes of carbon consisting of 60 (C60) or 70 (C70) carbon atoms arranged into a hollow cage of atoms.

**Graphene**—An allotrope of carbon arranged as a single-layer planar sheet of sp2 bonded carbon.

**Manufactured nanomaterials**—See Engineered nanomaterials.

**Metal oxide nanomaterials**—Nanomaterial that has a core composed of metal oxides.

**Nanocrystal**—Solid material whose constituent atoms, molecules, or ions are arranged in an orderly repeating pattern extending in all spatial dimensions, with at least one of these dimensions being less than 100 nm.

**Nanomaterial**—A material with at least one of its dimensions being less than 100 nm.

**Nanometer**—A unit of measure equal to $1 \times 10^{-9}$ meters.

**Nanoparticle**—A substance having all three dimensions less than 100 nm.

**Nanoscale**—The nanoscale refers to the size influence on the physical and chemical properties of materials as they are reduced from bulk material to particles having at least one dimension less than 100 nm. One example is the catalytic property of gold that only emerges as the particle size becomes nanoscale.

**Nanostructures**—See Nanoscale.

**Nanotechnology**—The study of engineering materials on the atomic or molecular scale.

**Nanotoxicology**—The study of the adverse effects of nanomaterials to organisms, populations, communities, and ecosystems.

**Nanotubes**—A nanometer-scale cylindrical structure made out of carbon, inorganics, phospholipids, nucleic acids, or proteins.

**Natural nanomaterials**—Nanoscale materials that are not produced through anthropogenic activities.

**Protein corona**—A particle coating consisting of adsorbed proteins effectively masking the core chemistry of the particle.

**Single-walled nanotubes**—A tube made from a single sheet of graphene.

**Size distribution**—A list of values or a mathematical function that defines the relative amounts of particles present, sorted according to size.

**Surface area**—A two-dimensional description of the exposed area of a solid object.

**Surface charge**—The electrical charge present at the interface of a particle and its environment.

**Surface chemistry/composition**—The physical and chemical phenomena that occur at the interface of two phases. The surface chemistry of a nanomaterial significantly influences its reactivity as well as its stability in an aqueous suspension.

**Surface modification/functionalization**—Chemical or physical modification of a nanomaterial that changes its surface chemistry, appearance, or reactivity.

**Zeta potential**—The electric potential in the interfacial double layer at the location of the slipping plane versus a point in the bulk fluid away from the interface. It is the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed nanomaterial.
References


