Guest Comment: Transformations of Nanomaterials in the Environment Focus Issue

Engineered nanomaterials (NM) are manufactured materials having at least one dimension in the nanoscale (ca 1–100 nm). Their small size results in a high percentage of surface atoms that give rise to properties and reactivity not observed from materials of identical composition but larger dimensions. As with the introduction of most new technologies, there is uncertainty with respect to the environmental impacts of engineered NMs. This uncertainty has prompted an increase in environmental health and safety (EHS) research aimed at assessing the potential for engineered NMs to harm the environment or human health. An overall goal of these research activities is to correlate the properties of NMs to their behavior in the environment and their effects on living organisms. Achieving this goal will require expertise for a wide range of disciplines and the advent of new tools for examining NMs in biological and environmental matrices.

The amalgamation of disciplines that make up the “nanotechnology” field makes it highly interdisciplinary. This diverse cohort of researchers create a growing new field of expertise, environmental nanotechnology. This discipline leverages expertise from a broad range of traditional disciplines (e.g., engineering, physics, chemistry, toxicology, biology, ecology) to look for ways to exploit the novel properties of nanomaterials for beneficial use while minimizing or preventing risk to human and environmental health. The tools and knowledge generated from 10 years of environmental nanotechnology research has coalesced into a new platform for understanding the role of nanophases in other fields of study, such as geology, medicine, and biology.

Underlying the effort to understand how NM behave in natural systems and how they may impact environmental and human health are several critical questions For example: How do the properties of NMs and their nanoscale features affect their behavior? How dynamic are NM properties in natural systems and how does the surrounding matrix affect the types and rates of transformations expected? What transformations are likely to occur and what stable products are expected in natural systems? How do the transformations affect the properties, behaviors, and potential for exposure to adverse effects of NM? The answers to these questions will improve understanding of how physical, chemical, and biological transformation of NMs arise through interaction in natural systems, a critical need for predicting risk and designing materials that avoid it.

The 20 papers included in this special issue begin to answer these questions and highlight the range of important environmental transformations that manufactured and natural NMs may undergo. Papers address how physical (aggregation) and chemical transformations impact transport and toxicity. They also elucidate the complex role that biological molecules and organic matter play in the transport and reactivity of nanomaterials (e.g., dissolution).

Aggregation can dramatically affect the transport characteristics and reactivity of engineered and natural NMs. Findings presented in this special issue demonstrate that aggregation influences NM mobility in natural waters and in model environmental porous media. For example, the extent of aggregation and the impact of aggregation on other processes (e.g., dissolution) depends on the composition of the media as well as the macromolecular coating on the NMs. Other authors present new theory that may be used to predict the aggregation of nanomaterials under various solution compositions and in the presence of organic matter. In all cases, organic macromolecules present on the nanomaterial surfaces or on the porous media (as biofilms) alter the attachment behavior and structure of the aggregates formed as well as the subsequent transport characteristics of the NM. Other authors demonstrate how aggregation decreases the reactivity of photoactive nanomaterials like ZnO and TiO2. The effect of aggregation on reactivity occurs at multiple scales; the macroscopic through shadowing of light, at the nanoscale through electron–hole pair interactions, and at the atomic scale through bonding structure modification.

Work presented in this special issue confirms that nanomaterials are highly reactive and dynamic in natural systems and reveal the importance of understanding how the altered properties of transformed NMs impact their fate, transport, and toxicity. The papers demonstrate a range of chemical transformations that nanomaterials experience, including chemisorption of toxic metal oxo-anions, complexation by organic molecules, and their subsequent dissolution and change in size and shape. In addition, aging (weathering) of nanoparticles affects dissolution and reactivity. The exchange of Fe(II) ions in solution with those deep in the crystalline structure of magnetite nanoparticles reveals the high reactivity of this metal oxide NM with elements in the surrounding fluid matrix. Other work describes the redox transformations of nanomaterials and the subsequent impact on the properties and behavior. Authors describe the oxidation of Cu and Cu-oxides, and the oxidation and subsequent sulfidation of Ag nanoparticles by inorganic sulfoxides and organic sulhydryl compounds in soils and freshwater sediments. One study correlates the properties of Ag nanoparticles (e.g., sizes and state of aggregation) with their propensity to sulfidize, and the subsequent impact on toxicity to E. coli. The issue also includes a review article that summarizes the range of environmental transformations of Ag nanoparticles and the impact of transformation on their toxicity to aquatic organisms.

The series of papers presented in this special issue highlight several transformations of natural and engineered nanomaterials that are critical processes affecting their behavior in the environment. It begins to make connections between the nanoscale properties and features of various NP types and their macromolecular coatings, and their behavior and effects in nature.
natural systems. The papers also illustrate that additional research and the development of novel tools for characterizing NMs in situ and at relevant concentrations is needed to more completely describe transformation processes and determine the extent to which these processes occur in real systems. The advent of such tools will present opportunity to fully understand the impacts of engineered nanomaterials in Earth’s critical zone and guide the design of materials that are benign in natural systems while retaining properties necessary for robust manufacturing and industry.

Gregory V. Lowry*
Kelvin B. Gregory
Simon C. Apte
Jamie R. Lead

**AUTHOR INFORMATION**

**Corresponding Author**
*E-mail: glowry@cmu.edu.

**Notes**
The authors declare no competing financial interest.

**Biographies**

Greg Lowry is a Professor of Environmental Engineering at Carnegie Mellon University in Pittsburgh, PA and Deputy Director of the Center for Environmental Implications of Nanotechnology (CEINT). He conducts multidisciplinary laboratory and field research in the emerging field of environmental nanotechnology. His work is aimed at understanding how a nanomaterial’s properties affect their fate and reactivity in the environment, and how these properties map onto their potential for exposure risk. Specific areas of interest include quantifying the effect of macromolecular coatings and natural organic matter on nanoparticle reactivity and attachment to surfaces, and the application of synchrotron-based X-ray techniques for characterizing biogeochemical transformations of nanomaterials in natural soils and sediment. He teaches courses on physicochemical processes of organic chemicals in aquatic systems, environmental engineering, and environmental nanotechnology. He currently serves on the National Research Council committee to develop a federal research strategy for environmental health and safety research for engineered nanomaterials.

Kelvin Gregory is an Associate Professor of Civil & Environmental Engineering at Carnegie Mellon University and an investigator at the Center for Environmental Implications of Nanotechnology (CEINT). His research explores the microbiology, ecology, and fundamental interactions between bacteria and their physical and geochemical environment. Within the field of environmental nanotechnology, research in Dr. Gregory’s laboratory aims to better understand how natural and engineered coatings and environmental transformations of nanomaterials affect their interactions with microbial populations.

Simon Apte leads the Contaminant Chemistry and Ecotoxicology Program at CSIRO Land and Water, Sydney Australia. His own research focuses on the speciation and toxicity of trace metals in natural water systems. He has conducted many investigations on the impacts of mining on aquatic environments in the Australia-Pacific region. More recently he has investigated the environmental transformations and ecotoxicity of zinc and cerium nanomaterials.

Jamie Lead is Professor of Environmental Nanoscience and Risk and Director of the Environmental Nanoscience and Risk SmartState Center at the University of South Carolina, and Adjunct Professor of Environmental Nanoscience and Director of the Facility for Environmental Nanoscience Analysis and Characterization, University of Birmingham, UK. His research aims to understand both natural and manufactured nanomaterial interactions, fate and impact in the environment and encompasses work from nanomaterial synthesis and characterization to risk and regulation.