

Nanotechnology in the Environment—The Good, the Bad, and the Ugly

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Nanotechnology is the ability to work at the molecular level, atom by atom, to create larger structures with fundamentally new molecular organization, novel properties, and functions. Engineered nanomaterials, typically a tenth the size of a human cell, are currently being used for a broad range of novel applications, including drug delivery, tissue engineering, tumor treatment, imaging, catalysis, detectors/sensors, and energy storage and transmission devices. Although some nanomaterials have been synthesized since the 1980s, their widespread production is relatively recent and their market size is expected to reach \$1 trillion within 10 to 15 years. Such rapid growth suggests the potential for large environmental footprints, some of which will be good, some bad, and some ugly.

On the good side, some nanomaterials hold great promise for reducing waste production, cleaning up industrial contamination, providing potable water, and improving the efficacy of energy production and use. The high potential to improve environmental technologies (some of which date back to the Victorian era) is intrinsically related to the small size of engineered nanomaterials, which results in significantly different properties than the associated bulk materials. Small size translates into a large surface to volume ratio, which implies greater opportunity to interact with environmental pollutants. In a sense, nanomaterials are “all surface.” This can be a highly desirable property for water, wastewater, and hazardous waste treatment. Some nanomaterials can be superior adsorbents or catalysts that remove pollutants more efficiently and at a substantially lower cost than current (material-intensive) approaches such as ion exchange resins and activated carbon adsorption. Nanotechnology also offers the potential for multifunctional materials, such as nano-architected membranes for water treatment that incorporate chemically reactive nanomaterials to accomplish both separation and degradation of pollutants and enhance antifouling properties. The good news is that many of our colleagues are making significant progress toward the development of environmental nanotechnologies. These include nanosized iron for reductive treatment of chlorinated solvent DNAPLs, nanomagnetite for the removal of arsenic by sorption and magnetic separation, high-performance nanoscale (Pd/Au) catalysts for treating particularly challenging contaminants in water that must be removed to a very low level, and novel advanced oxidation and disinfection approaches, to name a few. We hope to publish more papers in these emerging areas of research in the near future.

On the *bad* side, the environment will be increasingly prone to

suffer pollution from nanomaterials in consumer products such as sunscreens, detergents, and cosmetics, as well from accidental releases during production, transportation, and disposal operations. Thus, engineered nanomaterials could become a new class of pollutants, and questions about their transport, fate, reactivity, bioavailability, and toxicity will become increasingly important. The small size of such materials implies greater risk of uptake (e.g., by breathing) and interacting with sensitive organs or ecosystem components. Some nanomaterials have already been reported to be toxic to humans, fish, and bacteria. This raises concerns not only about public health (e.g., related to occupational exposure) but also about broader environmental impacts (e.g., bioaccumulation in food webs and disruption of bacterial activities that are important to the health of all known ecosystems and biogeochemical cycles).

Many examples in modern history illustrate the unintended consequences of initially promising technologies, including the blind release of “beneficial” chemicals, such as chlorofluorocarbons, DDT, and MtBE into the environment. These examples forewarn us of potential environmental impacts of some nanomaterials, which deserve more attention and research. However, on the *ugly* side, the manufacture, use, and disposal of engineered nanomaterials are not regulated, mainly due to a lack of ecotoxicological information and the novelty of the field. Thus, there is an urgent need to create and disseminate information about the environmental implications of nanotechnology so that its growth does not continue to outpace the development of appropriate regulations to mitigate potential risks. Furthermore, the large intellectual and financial investments in nanotechnology demand that it be publicly accepted and sustainable. The backlash against genetically modified crops resulted in a huge setback for agriculture. A similar backlash against nanotechnology would result in the delay of beneficial nanomaterials coming to market.

In conclusion, it is important to capitalize on the leapfrogging opportunities offered by nanotechnology to improve and protect environmental quality. Yet, responsible uses of nanomaterials in commercial products and environmental applications, as well as prudent management of the associated risks, require a better understanding of their mobility, bioavailability, and impacts to a wide variety of organisms. Responding to questions on environmental impacts of nanotechnology in the early stages of its development may result in better, safer products and less long-term liability for industry. Indeed, due diligence is needed to ensure that nanotechnology evolves as a tool to improve material and social conditions without exceeding the ecological capabilities that support them.