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Manufactured nanoparticles in the environment

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Environmental context. Nanotechnology is a very important industry which may be socially transformative, but produces nanomaterials (NMs) which have a potential but poorly characterised risk to the environment. This Research Front describes new research investigating NM environmental chemistry, particularly in relation to ecotoxicology. This Research Front shows some of the most exciting research undertaken currently and fits within a dynamic research program, which is global in scope and which attempts to unravel these complex areas.

Manufactured nanoparticles (MNPs) can be defined as materials having all three dimensions between 1 and 100 nm in size and are a subset of nanomaterials (NMs), which have at least one dimension within this size range.[1] There are two parts to this definition that define their source and size, both of which raise important points. The word ‘manufactured’ (particles are sometimes called synthesised or engineered) implies that they are deliberately produced by human activity for specific purposes and distinguishes these nanoparticles from incidental NPs that are produced as a side product of human activity, for example from industrial processes or transport, and from natural NPs, for example humic substances, produced from weathering, microbial action or chemical hydrolysis. Further discussion of all these nanoparticle types can be found elsewhere[2–4] and the large number of recent reviews on these subjects reflects their current importance and the scientific progress being made.

The source of the nanoparticles is important and there is some confusion in the literature because of the incorrect application of the term ‘nanoparticle’. For instance, natural NPs are of most importance in aquatic and terrestrial environments, whereas incidental NPs are primarily important in the atmosphere and MNPs are potentially important in all compartments, but aquatic systems are currently most studied. The main reason for attempting to understand natural NPs is their impact on natural processes, for example pollutant speciation and weathering, biofilm development, etc., whereas incidental NPs are studied primarily for their direct human health effects via respiratory uptake and impact on the respiratory and cardio-vascular system. The main focus of MNP risk research has been in certain areas such as occupational health, human toxicology and ecotoxicology, with chemistry and environmental fate issues less studied. Nevertheless there is a growing appreciation that such exposure and uptake related issues are of critical importance. Finally, there is a large body of information on incidental NPs (ultrafines) and natural NPs (natural colloids, which includes the nano-sized material but also incorporates a larger size fraction) which can be used, with caution, in helping to understand the issues of MNPs. Caution is required because natural NPs and incidental NPs are, in general, structurally and chemically far more complex than MNPs. In addition, paradigms from one area, for example oxidative stress as the main toxicological mechanism of action of incidental NPs in humans, require supporting evidence before application to other areas such as the ecotoxicology of MNPs.

The size requirement seems simple enough conceptually, but leads to further interesting complexity.[5] For instance, how do we treat nanostructured surfaces or aggregates of nanoparticles whose total size is not in the nano range? Although size is a useful guide, a better conceptual definition of ‘nano’ is that size at which novel properties and processes manifest themselves. This definition is difficult to use by regulators and standards organisations, but is scientifically extremely useful in allowing a greater freedom to pursue relevant and interesting questions. Nevertheless, this issue has practical implications for regulators in defining whether a substance can be thought of as ‘new’ or ‘existing’; the implications of this categorisation for control of potentially hazardous substances is large, with new materials being treated far more stringently in many cases.

Despite the presence of large amounts of natural NPs and incidental NPs in the environment and the existence of small amounts of MNPs for at least several thousand years, the recent concerns over risks of MNPs are due to several factors: we have a greater control than ever in producing nanoscale materials and in the organisation of structures and chemistry at the nanoscale; the materials which are produced are often novel, for example carbon nanotubes, which have no natural analogue; there is an enormous potential for the technology to be widely available and socially transformative; and there are potentially large but largely unknown risks associated with the materials. In the last few years, the first wave of this technology has become available and there has been a widespread use of MNPs. Uses have included

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those which can be considered very important such as environmental remediation and the use of catalysts which are added to diesel to improve fuel efficiency and so reduce oil use and pollution. Other, often widespread, uses can be considered to be far less important and sometimes bordering on the frivolous or dangerous or both. The use of bacteriocides in most consumer goods would fit into this category. Nevertheless, current MNPs are largely passive and there are enormous possibilities for 'next generation' MNPs which might be physiologically active and self-organising. An excellent current example is the potential in nanomedicine and research at the nano-bio interface. Nanoparticles which are designed both to be able to cross biological barriers and to carry other compounds as used in drug delivery have many potential benefits but have equally obvious hazards associated with their use. The next decade or two promise to be interesting times.

The current situation in nanotechnology and nanoscience is one in which there is great potential for benefit but an equally great uncertainty in associated risks. There is evidence for both optimism and pessimism here. Pessimism is due because of the huge discrepancy between the scale of research being performed on the production of new processes and materials and that performed on their attendant risks. Optimism is due because of the uniquely forward-looking attitude of policy makers and regulators. Comparison of the current situation with the development of other new 'wonder' materials such as PCBs and asbestos gives perspective and this is perhaps the first new chemical or material type to have undergone such intense, systematic and coordinated action before any hazard being demonstrated. However, it is clear that such forward thinking was justified as environmental effects have been shown[6] and direct, observable human health effects have very recently been observed in Chinese workers.[7]

High quality science is required to drive forward our understanding and we hope this Research Front published by *Environmental Chemistry* will help here. This issue contains examples of some of the best science currently being performed in this area. The Research Front begins with the Highlight by Arugete and Hochella,[8] which considers the important factors in microbial–NP interactions, including both microbe- and NP-specific factors. A Review by Chen[9] further considers the colloidal and surface chemistry of nanoparticles, focussing on carbon-based NMs and their implications. Aruguete et al. then present research findings discussing quantum dot effects on single species bacterial strains.[10] Taken together, these papers show the need for well controlled and characterised NPs in short-term, laboratory experiments. Further research in more complex but less easily interpreted conditions is required alongside these important laboratory based experiments. The next two papers by Scown et al.[11] and Rogers et al.[12] show further ecotoxicological data for fish and algae respectively using commercially available but well characterised metal oxides nanoparticles and discuss mechanisms of action (algae) and uptake (fish). Domingos et al.[13] then discuss the impacts of environmentally relevant conditions such as pH, ionic strength, phosphate concentration and humic substances on the surface properties and aggregation of commercially available inorganic nanoparticles. Surprising and complex interactions are revealed primarily by the relatively new method of fluorescence correlation spectroscopy (FCS). Finally, further methodological development is demonstrated by Gallego-Urrea et al.,[14] who test the utility of a newly commercially available technique for particle counting and sizing and discuss its application to NPs in the natural environment. Finally, although not formally part of the Research Front, a paper by Plathe et al.[15] is worthy of mention here, as a detailed study of natural nanoparticles which help to set the scene for the study of manufactured nanoparticles.

As these papers demonstrate, there is much high quality and novel science being performed in this area. Although there are challenges in understanding the risks and behaviour of nanoparticles, and new potential risks arrive with new developments, the field has a vitality and maturity which indicates these challenges will be met with enthusiasm.

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