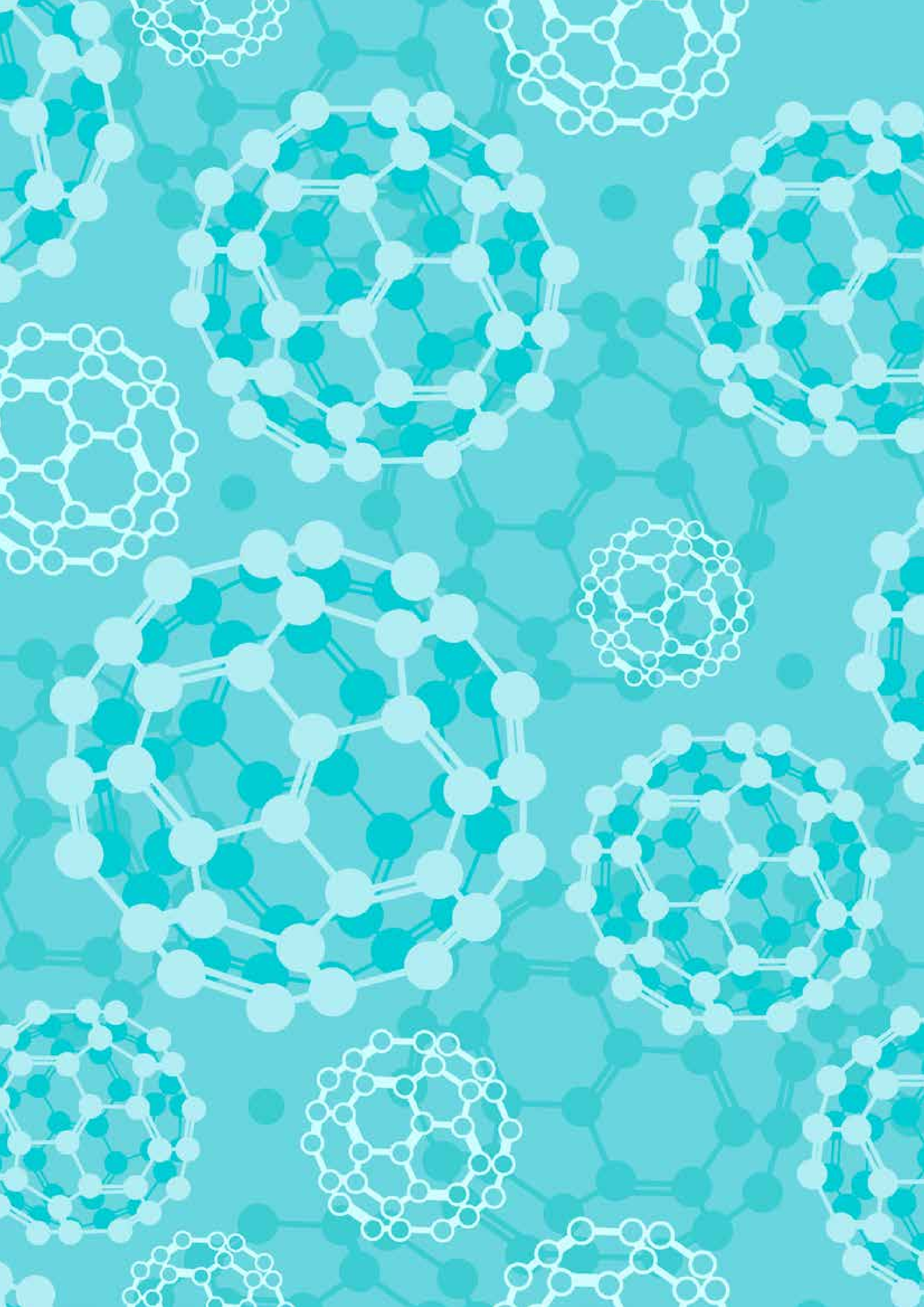
Environmental Nanoscience Initiative

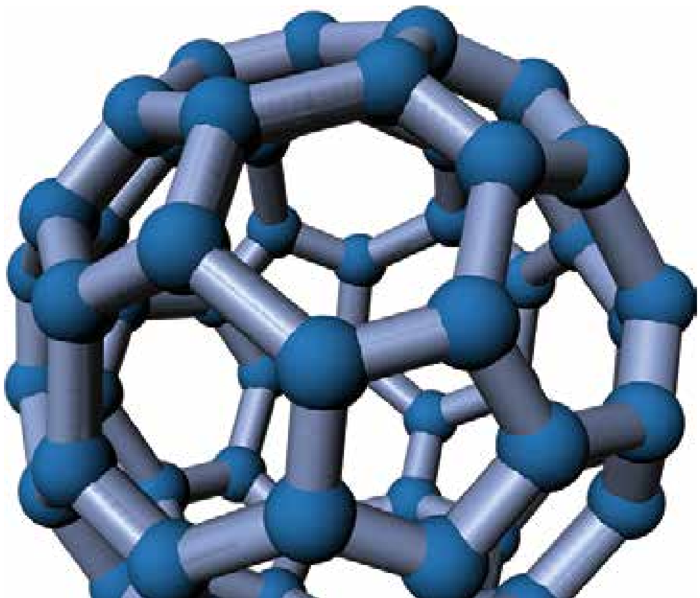
Fate, behaviour and impacts of nanomaterials in the environment: a UK – US research programme

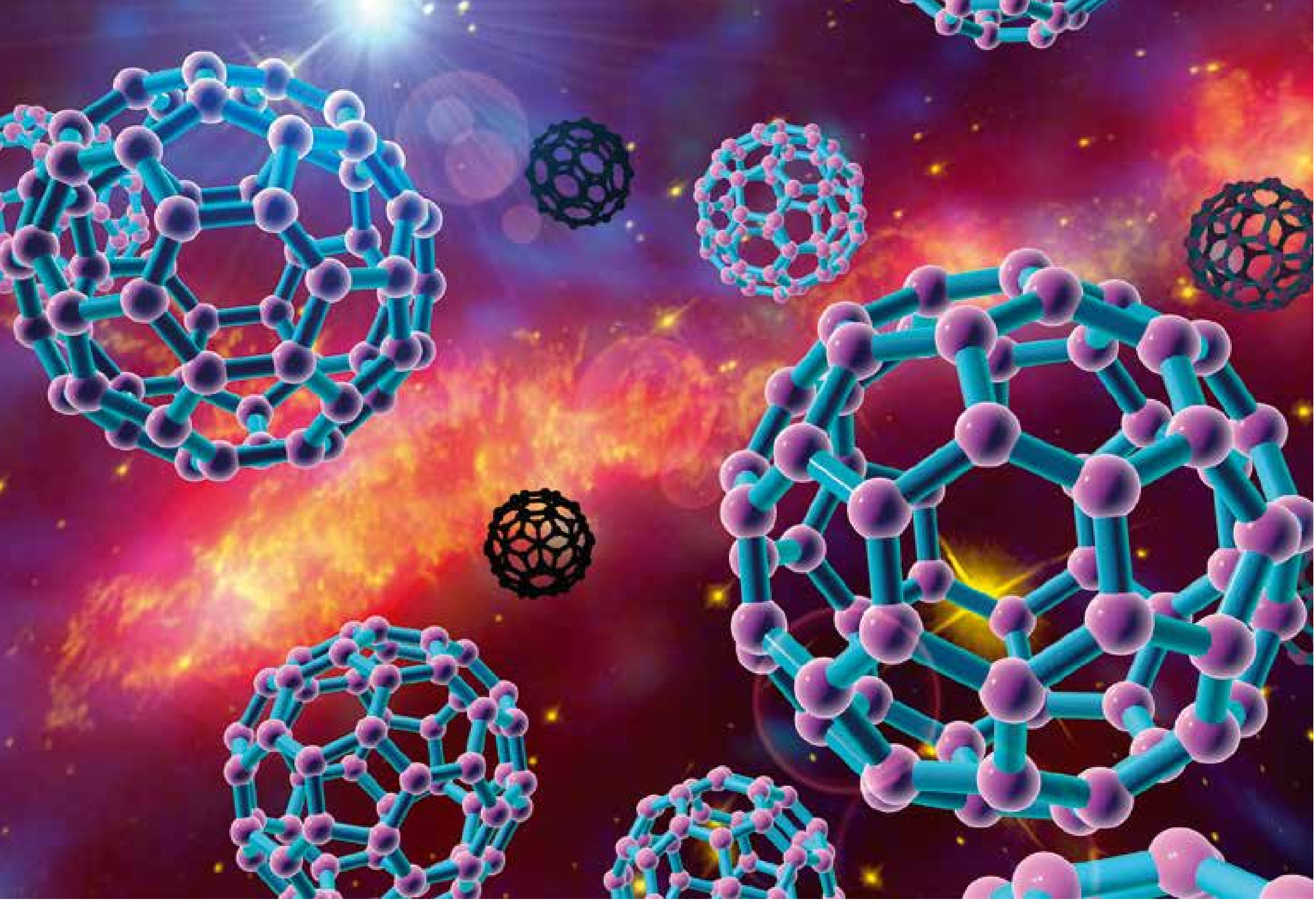
Natural Environment Research Council; Department for Environment, Food and Rural Affairs; Engineering and Physical Sciences Research Council; Biotechnology and Biological Sciences Research Council; Medical Research Council; Department of Health; and the Environment Agency in conjunction with US Environmental Protection Agency and US Consumer Product Safety Commission



Contents

Front cover image: Glynn Gorick





Introduction

Nanoscience, the science of the very small (a billionth of a metre), is supporting the growth of a technology predicted to be worth many billions of pounds within a decade.

In 2004 the Royal Society and Royal Academy of Engineering published a seminal report assessing the opportunities and potential risks of a new wave of technological applications based on materials manufactured at the nanoscale – a billionth of a metre. New nanomaterials such as carbon nanotubes that exploited unique physical and chemical properties at these scales were being produced, with potentially huge economic, health and environmental implications. Consumer products were already appearing on the market. Nano was not a technology of the future, it was already here.

The Royal Society and Royal Academy of Engineering report drew on existing research on unintentionally-produced nanoparticles (for example in atmospheric pollution ('ultrafines'), coal dust and asbestos). It also focused attention on the possible health and environmental risks that novel manufactured nanomaterials might pose. The report highlighted how little we knew about how manufactured nanomaterials could enter the environment, how they might behave, their fate, and their possible effects on plants, animals and humans.

In response the research councils, led by NERC, along with the Department of Environment, Food and Rural Affairs (Defra), the Department of Health and the Environment Agency, established a programme of research on hazard, exposure and risks, including scientific understanding of how these novel nanomaterials interact with the environment. The Environmental Nanoscience Initiative (ENI) was born.

It soon became clear that before research could begin in earnest, the UK needed to build a community of scientists who could respond to the challenge. There were already some scientists working on naturally-occurring nanomaterials (e.g., colloids in aquatic systems), but overall this community did not exist.

“…truly integrated, trans-Atlantic teams of scientists working together…”

In 2006 the ENI announced the first of two calls for small, exploratory research proposals. These funded ten projects investigating the fate and behaviour of nanomaterials in surface and ground water, their impacts on fish and invertebrates in aquatic and soil ecosystems and new methods for visualising the particles in plants. A second call in 2007 resulted in a further seven funded projects specifically looking at nanomaterials' impact on microbial communities in soils, sediments and water. This first phase was designed to build capacity and pump prime research, creating a community of scientists who could use their data to develop larger proposals, for example to the EU's Framework Programme.

Building on the successes of the first phase, plans for a second began to emerge. It was clear from discussions with many stakeholders that a major goal for this stage of the programme should be developing models to predict the fate, behaviour, bioaccumulation and effects of nanomaterials through different pathways of exposure in the environment,


Rothamsted Research

Bacteria treated with engineered nanoparticles.

in the air, water and land. This would need to be underpinned and validated by robust, high-quality scientific evidence. But the sheer diversity of nanomaterials and the complexity of their potential behaviour, biogeochemistry and biological interactions in the environment made this an ambitious challenge. To meet it, an international endeavour pooling expertise, skills and knowledge across continents would be needed. In 2008 NERC led the development of a far larger bilateral research programme with the US, with the existing funders in the UK being joined by the US Environmental Protection Agency and Consumer Product Safety Commission.

The programme launched a major call for proposals in 2009, and three large, interdisciplinary UK-US consortia were funded. These would not be loose coalitions of researchers working in parallel, but truly integrated, trans-Atlantic teams of scientists working together. The ENI pioneered this international way of working in response to complex environmental challenges. The sheer volume of high-quality scientific publications listed in the annex to this brochure is just one testament to how successful this has been.

The rest of this brochure presents the research undertaken by these three large consortia. The RAMNUC consortium focused on impacts of nanomaterials from consumer products (e.g., household sprays) and diesel fuel additives on human health via the atmosphere. Research by the TINE consortium concentrated on nanomaterials entering wastewater treatment plants, their partitioning to sewage sludge and effects after application of this to soils. The NanoBEE consortium also investigated nanomaterials in sewage plants, but its main focus was the behaviour and impacts of nanomaterials in rivers and other freshwater ecosystems.

To responsibly develop and realise nanotechnology innovations, we need to understand the risks to environment and health they may produce. This in turn requires robust scientific information about the environmental fate, behaviour and impacts of nanomaterials, and robust tools such as models to support decision-making. This is a long-term process, to which the work supported by the ENI has made an invaluable contribution. It has helped build an internationally-recognised community of scientists, fostered real and lasting international collaboration, and – ultimately – made a useful and very significant contribution to knowledge.

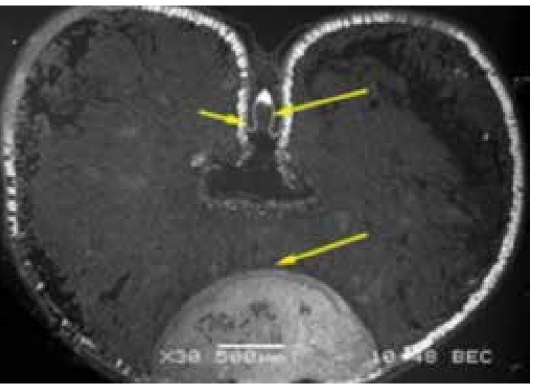
Sophie Rocks
Knowledge Exchange Fellow, Environmental Nanoscience Initiative

Richard Owen
Environmental Nanoscience Initiative Coordinator

Sewage treatment plant at Cranfield University (UK) showing the closed systems used to treat sewage with nanomaterials (TINE consortium).

Nanomaterials
in the terrestrial environment

Wheat growth and uptake experiments with sewage sludge treated soil and electron micrograph of wheat grain showing deposition of zinc.



Rothamsted Research

A major gap in our current knowledge is how nanomaterials are introduced into the terrestrial environment, their fate and behaviour there and how they can affect wildlife and human health, for example via the food chain. This has been the primary focus of the TINE consortium (Transatlantic Initiative for Nanomaterials in the Environment), which includes researchers from Rothamsted Research, the Centre for Ecology and Hydrology, Lancaster and Cranfield Universities in the UK and the University of Kentucky, Duke University and Carnegie Mellon University in the US.

One major potential route by which manufactured nanomaterials (e.g., those used in consumer products) enter terrestrial ecosystems is via sewage treatment plants, since in many countries the biosolids (sludge) produced in these works are applied to land to enhance crop growth. The consortium identified several important questions to answer – how zinc, titanium dioxide and silver nanoparticles behave during sewage treatment, how much (and in what form) they become incorporated in sludge, and how they affect soil communities, plants and humans via the food chain.

The researchers have compared the transport, behaviour, bioavailability, and effects of 'pure' metal nanoparticles, metal nanoparticles in 'aged' form (those left exposed to the environment for a period of time), and dissolved free metals to determine whether the effects are due to the nanoparticle or the metal itself. They have looked at organisms that perform key functions in terrestrial ecosystems, and compared the impacts of nanomaterials with those of the same substances in larger (so called 'bulk') forms. Another focus has been exposure pathways involving humans. The consortium has also considered how different materials behave in the aquatic environment and how the physicochemical properties of the materials influence this behaviour. The findings have been used to develop models showing how the fate of nanomaterials through sewage treatment plants influences their transfer to the terrestrial environment and how this would affect important organisms. A key output has been a first generation 'Life-Cycle-Analysis-inspired Risk Assessment' (LCA-RA) model for the impacts of nanomaterials and aged nanomaterials in the terrestrial environment.

Fate and behaviour in sewage treatment plants and soils

During manufacturing, industrial and household use of nanomaterials, some may escape into sewage. Using a unique pilot sewage treatment plant developed at Cranfield University, researchers investigated the behaviour and fate of nanomaterials. Sewage treatment systems were designed to generate biosolids which contained bulk metal or nano-metal (at the regulatory limit for zinc in biosolids and the equivalent for titanium and silver which are not currently regulated), so as to understand the behaviour and effects of nanomaterial containing biosolids when applied to soils and compare this with untreated biosolids.

The researchers found that the nanomaterials in the sewage treatment plant mostly ended up in the sewage sludge, with low concentrations in the effluents of the treatment process. Nanomaterial forms of silver or zinc oxide did not remain as intact particles, being completely transformed within the treatment plant.

The consortium also investigated what happens when biosolids containing nanomaterials were applied to soils. In a small-scale study, researchers spiked biosolids obtained from a wastewater treatment plant in Lexington, Kentucky with silver nanomaterials with a variety of particle surface coatings. They then applied these biosolids to soils and aged them for up to two months before comparing them with the results of spiking soil directly with unaged silver nanomaterials. They found that, while the particle coating affected the nanomaterials' movement in the environment when spiked directly into the soil, the aged nanomaterials behaved identically irrespective of the particles' coating. This demonstrates how the transformations during wastewater treatment can negate the influence of the initial particle coatings on nanomaterial behaviour.

Researchers at Rothamsted Research further studied the behaviour of nanomaterials in soils and crops, and compared their behaviour with that of bulk materials. They found that silver from nanomaterial-treated biosolids gave higher concentrations in drainage water than bulk silver treated biosolids in the first three months, but over six months they were similar and the overall rates of leaching were low. Common soil extraction protocols for predicting mobility and bioavailability in the environment suggested that these were similar for the nanoparticulate metals and the bulk metals in biosolids.

Impacts on soil communities and plants

TINE researchers also looked at the toxicity and metal bioaccumulation of nanoparticle-treated biosolids. They have shown that barrel clover grows less, has fewer nodules, and accumulates more zinc when exposed to aged nanomaterial-treated biosolids compared with the bulk-treated biosolids. Patterns of gene expression and the behaviour of the soil microbial community were significantly altered by the nanomaterial-treated biosolids. Wheat grown in the nanoparticle-treated biosolids had a similar final mass to that grown in the bulk-treated biosolids, and there was no evidence that nanoparticles had migrated into the wheat grain. Earthworms in the nanoparticle–treated biosolids reproduced less than earthworms in the bulk-treated biosolids. Calculations suggest that this was more likely to be due to zinc than to silver or titanium. Overall, the results suggest that current risk assessment approaches may not give enough protection against zinc oxide nanoparticles that are introduced into sewage treatment plants. Further studies at lower concentrations are underway.

Key soil organisms, such as nematode worms, have been studied to compare the bioavailability and toxicity of laboratory-aged nanomaterials with 'pristine' nanomaterials. These studies demonstrated that aged nanomaterials are considerably less toxic than pristine nanomaterials, with lower metal uptake, smaller effects on growth, mortality and reproduction, and different patterns of gene expression. Therefore ecotoxicity tests using pristine nanomaterials may not accurately predict the toxicity of these materials once they have been transformed in the environment.

Models to support risk characterisation

Models to support risk characterisation and decision making are a significant output from the TINE consortium. The team have developed an existing model of chemical transport through watersheds to describe the transport of silver and zinc oxide nanomaterials and their products from farmland and into and through a river system. The model takes into account how land-use patterns, topography, meteorology and stream hydrology influence the transport and fate of the nanomaterials.

The researchers also produced a Bayesian risk forecasting model to predict the toxicity of silver nanomaterials. The model provides a robust method for formally incorporating expert judgments into a probabilistic measure of exposure to and risk from nanomaterials. It can be easily adapted and updated as additional experimental data and other information on nanomaterial behaviour in the environment becomes available.

A further output was a novel, functional assay-based approach for predicting fate and effects of nanomaterials. These tests incorporate nanomaterial properties and environmental parameters which are known to be predictive of their transport in the terrestrial environment, bioavailability and toxicity.

Dr Thomas Ashton

Nanomaterials
in the aquatic environment

During manufacture, nanomaterials are likely to be introduced directly or indirectly into the aquatic environment. Researchers within the NanoBEE (Manufactured Nanoparticle Bioavailability and Environmental Exposure) consortium have investigated the environmental fate and biological impacts of a range of important nanomaterials, researching their inputs, interactions and behaviour over time. The team, including researchers from University of Birmingham, University of Exeter, and Herriot Watt University in the UK and Clemson University, University of California, and Rice University in US along with the US Geological Survey, studied a range of nanoparticles (including silver, ceria, zinc oxide and gold) with different sizes, surface chemistries and coatings and shapes.

The consortium studied the bioavailability and toxicity of these nanoparticles in a range of aquatic organisms, from bacteria to fish, using both targeted toxicological assays and non-targeted (transcriptomic and metabolomics) approaches. They further developed and validated models that predict nanomaterial exposure, bioavailability and toxicity to support hazard and risk assessment.

Freshwater snail Lymnaea stagnalis.

NanoBEE consortium

Development of a nanomaterial library

An important element of the team's work was to produce a library of nanomaterials of known physical and chemical properties, including their chemistry, shape, and size. These well–characterised 'pure' materials were then used to test whether the nanomaterials' shape, size, chemistry or other properties were linked to bioavailability and harmful effects.

The methods used were designed to reduce or eliminate potential contaminants that may affect toxicological testing – for example, organic solvents were eliminated from manufacturing methods as these can alter the behaviour and toxicity of the nanomaterials. The consortium developed isotopically-labelled nanomaterials to track nanoparticles' movement within environmental systems and organisms, and further developed methods for clearly visualising nanomaterials. This allowed the researchers to produce 3D reconstructions of nanomaterials and their interactions with proteins, to form coatings, and other biological matrices.

Understanding environmental fate and behaviour

An important part of NanoBEE was to adapt and validate computer models that predict how a nanomaterial moves between different parts of the environment. Since the lack of good-quality data is a major obstacle for validating these models, the team studied gold nanoparticles used in medical applications where the uses are more clearly defined and certainty about data is greater. Even so there were significant challenges in obtaining data but, despite this, the modelling suggested that for this particular field of application there is unlikely to be substantial environmental exposure or risk in the medium term.

The researchers built small laboratory simulators for wastewater and surface water systems, and used them to examine and characterise the fate, transformation and behaviour of silver nanomaterials in the environment. Knowing what form a nanomaterial takes in the environment is important to understand exposure, uptake in organisms and likely ecotoxicological impacts. In wastewater systems and surface waters, both synthetic and environmental coatings were found to play a significant role in persistence of the nanomaterial. The presence of either a polymer coating or a natural organic coating on the nanomaterial increased its stability and slowed aggregation of particles, suggesting that the material coating (either manufactured or naturally-occurring) is likely to affect its behaviour and transport of materials within the system.

In further studies at realistic environmental concentrations of nanoparticles, the relative importance of dissolution and aggregation changed when compared with higher concentrations. At high concentrations, much used in previous environmental research, aggregation is significant. Yet at lower concentrations, which are environmentally realistic, dissolution of silver nanomaterials to silver ions was found to be more important and particle aggregation less important. The speed at which aggregation takes place is directly related to particle concentration; reduced aggregation maintained the particle's high specific surface area which promoted dissolution.

Bioavailability, bioaccumulation and toxicity

The NanoBEE consortium used models to design experiments aimed at studying the influence of nanoparticle concentration, water quality, and coatings on the bioavailability and toxicity of a range of nanomaterials and non-nanomaterial metal salts.

Labelled silver nanoparticles in water and in feed were used to investigate the concentration-dependent uptake of silver in freshwater snails. The accumulation of silver from nanoparticles was detected in tissues at low concentrations in water or feed, with uptake rates being largely linear over a wide range of particle concentrations. At low waterborne concentrations most of the silver came from the dissolved nanoparticles, but at higher concentrations 80% of the bioaccumulated silver originated from the particles themselves. The noted differences in behaviour between the non-nanomaterial salt and the nanoparticles were observed under a range of conditions and suggest that a nano-specific mechanism of uptake may occur. These studies will be further examined to provide detailed transcriptomic and metabolomic profiles of organisms to investigate mechanisms of action.

The NanoBEE team also investigated uptake rate across a range of different water qualities, including the hardness of the water, which they found significantly affected bioavailability from waterborne silver nanoparticles when compared with that of silver ions. However, experiments showed that water hardness had no effect on silver delivery from silver nanoparticles presented in the diet. Uptake of silver from nanoparticles was either increased or not strongly affected by the presence of naturally-occurring organic material such as humic acids but was substantially reduced by cysteine which is found in many proteins due to the creation of a soluble silver-cysteine complex that, in turn, reduced the bioavailability of the nanoparticles.

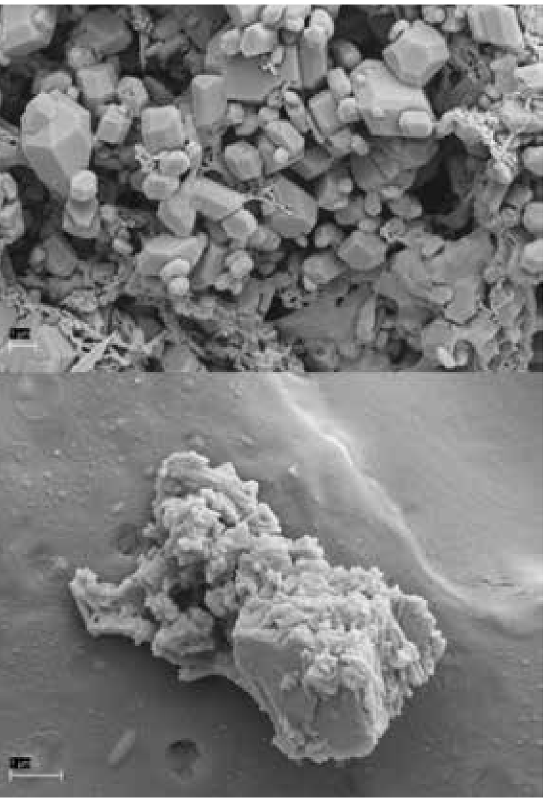
The same model organisms and particles were used for bioavailability and toxicity studies, allowing links to be made between the two. Bioavailability is almost by definition a precursor to toxicity, but the linkages are complex due to nanoparticle transformation and the diversity of possible exposure routes. Substantial amounts of research have been performed to understand the relative roles of waterborne and diet-borne uptake and toxicity, as diet is often a key mode of exposure. Toxicity and mechanism of toxicity differences between inorganic nanoparticles and both larger particles and dissolved phase metals have been partially explained.

The researchers used their data on nanomaterial fate and transformation in wastewater treatment systems to develop validated models of fate and behaviour (dissolution, aggregation, diffusion) in freshwater systems. In a simplified freshwater food chain comprising of the green alga *Chlorella vulgaris* and the crustacean *Daphnia magna*, silver nanoparticles had lower uptake rates than the dissolved silver and showed a similar reduction in toxicity. In general, higher uptake values in alga were related to higher toxicity, and electron microscopy was used to show the presence of silver nanoparticles in alga when exposed to higher nanoparticle concentrations. Dietary update of silver by daphnia was possible for both aqueous and particulate forms of silver. A detailed investigation of a range of organisms, including bacteria, algae, daphnia and fish, provided information on the links between nanomaterial characterisation and dose, biouptake and toxicity.

Investigating

public health risks from atmospheric exposure

Electron micrographs showing nanoparticle structures for two nanotechnology-based consumer sprays containing zinc oxide.



RAMNUC consortium

A consortium involving the National Heart and Lung Institute and the Department of Materials at Imperial College London, and Rutgers University and Duke University in the US has researched human health risks associated with atmospheric exposure to manufactured nanoparticles. The RAMNUC team (Risk Assessment for Manufactured Nanoparticles used in Consumer Products), working in partnership with Public Health England, used a range of experimental and computational approaches to understand and predict environment and health risks associated with nanoparticles. It focused on zinc oxide and silver nanoparticles readily available in consumer sprays, and ceria nanoparticles present in diesel fuel additives. The team wanted to understand how toxicity of these nanoparticles, which occur as complex mixtures in consumer products, change (for example, by agglomeration) as they enter and move through the atmosphere and become inhaled, and how this affects their toxicology particularly through the inhaled route into the lungs.

Fate and behaviour of nanoparticles in consumer spray products

Many consumer products containing nanomaterials are available on the market. Humans are also exposed to a wide range of naturally-occurring and anthropogenic (due to human activity) particles every day, for example from vehicle exhausts. The consortium studied five household sprays (used as cleaning products, sun screen, skin anti-fungicides, and dietary supplements) and found that consumers may be exposed to a wide range of particle sizes. However, for most of these sprays, consumers are likely to inhale particles larger than 100 nm. Aerosol nanoparticles (14-100 nm) were released from all of the sprays, but these were found to occur at lower mass concentrations.

The researchers undertook a study in which cosmetic powders were applied to the face of a human mannequin. They found that exposure would be predominantly to agglomerated particles larger than 1-100 nm. At this size range, this would suggest that nanomaterials would predominantly be deposited in the airways in the head and tracheobronchial regions, rather than in the deeper alveolar regions of the lung, as would be expected for smaller nanoparticles and would reduce the potential for the particles to enter the blood stream.

They also found that bioreactivity in lung cells isolated from human lung tissue varied with both the type of particle (e.g., zinc oxide or silver) and the carrier solution in which these occurred. Using a combination of advanced characterisation techniques and cell viability assays, the group has characterised how the engineered nanomaterials dissolve and transform in different environments (such as differing acid, proteins and salt conditions) and following incubation with cells. For example, the lung lining fluid, and particularly compounds within lung surfactants, can reduce the aggregation of nanoparticles and can delay silver ion release, while inside the human alveolar cells, silver nanowires can be dissolved and subsequently transformed into the highly insoluble silver sulphide.

When the lung cells were exposed to a commercially-available antifungal spray consisting of nanoparticulate silver suspended in water, toxic effects were not observed; neither were they observed when the nano-silver and water were separated from each other and tested alone. However, when a commercially-available cleaning product, also containing nanosilver, was tested, it exhibited significant toxic effects. These effects reflected a combination of increased inflammatory response due to the cleaning product solvent alone and reduced cell viability due to the silver nanoparticles alone.

The solvent-dependent effect demonstrates the importance of testing nanomaterials as they occur in commercial products themselves, as experienced by the consumer, as well as in isolation. A similar finding was reported for zinc-containing sprays, where the relative toxicity of the whole product, the zinc nanoparticles alone and the solvent carrier alone, varied between products and depended on the type of spray involved. Overall these studies suggest that inhalation of nanoparticle-containing sprays could damage health and that the particle size and solvent used in the product may also change the fate, behaviour and toxicity of the particles in these products.

Impacts of nanoparticle-containing fuel additives

A second focus for the RAMNUC consortium was to investigate the fate, behaviour and toxicological effects of ceria nanoparticles that are added to diesel fuels to improve fuel combustion efficiency. Researchers studied the impact of a commercial nanoparticle-containing additive on the emission of particulate and gaseous pollutants from a single-cylinder, four-cycle diesel engine. They found that adding ceria reduced certain harmful emissions (including carbon monoxide, carbon dioxide, total particle mass, formaldehyde, acetaldehyde, acrolein and several polycyclic hydrocarbons) and increased emissions of nitric oxide and nitrogen dioxide. However, there was also an increase in the number of ultrafine particles emitted per unit electricity generated by the engine.

When cultured human lung cells were exposed to ceria-containing diesel exhaust particulates the inflammatory response was reduced compared with those from untreated diesel, particularly at the higher concentrations of the ceria, suggesting an anti-inflammatory action. The RAMNUC group also found that variability in the innate immune responses in white blood cells (monocytes) was linked to changes in size and electrostatic charges of the diesel exhaust particulates induced by the presence of ceria. Further in vivo work showed that ceria-containing exhaust particulates caused less lung inflammation than exhaust particulates from untreated diesel, suggesting that the addition of ceria-based fuel additive resulted in particulate emissions that caused less inflammatory effects in the lung.

Modelling toxicity and health risks

The sheer number of products and applications containing nanoparticles, the equally diverse potential routes of exposure in the environment and the vast range of organisms that could be affected, poses significant challenges for understanding the health risks they pose. This is compounded by the physical and chemical changes nanoparticles undergo when they occur as complex mixtures – both in the products themselves and when they enter the environment. The RAMNUC team took a modular modelling approach that includes use of a geographic information system (GIS) and particle size data to identify possible exposure to silver nanoparticles in both indoor and outdoor environments, in order to capture realistic exposure scenarios at a population level. This was combined with predictions of biological responses at the level of cellular and lung function (e.g., airway resistance) using age-relevant physiological data to understand how the uptake of nanoparticles and the doses received by different parts of the body varies across populations.

The team has also developed models of particle fate, behaviour and toxicity in vitro, using a computer model of how cells interact with nanoparticles derived from data collected from human cell culture systems. This can be used to analyse the effects of nanoparticles on living cells by predicting changes in their cellular mechanisms. They have also modelled the effects of nanoparticles throughout the lung to provide estimates of particle transport across the air and biological fluid interface and the final expected dose for both coated and uncoated particles.

The RAMNUC project emphasises the importance of characterising exposure to nanomaterials at the point of source as well as in the final commercial product as the toxicity of these products should be taken as a whole and not only focused on only the nanoparticle component or the nanoparticles in the form that they were when initially added to the products.

Legacy

Research under the Environmental Nanoscience Initiative, in parallel with other funded projects, has provided important fundamental understanding of how nanomaterials enter and move through the natural environment, how they change in the environment and how they might affect plants, animals and human health. The science it has supported has been of the highest quality. The ENI has played a major role in building an international community of world-leading environmental nanoscientists, developing a way of working collaboratively across continents and disciplines. In this respect, much has been achieved since the Royal Society and Royal Academy report of 2004.

In truth this journey is still ongoing, as the sheer diversity of nanomaterials and the complexity of their behaviour and interactions in the environment presents a daunting, but not insurmountable, challenge. When manufactured nanomaterials enter the environment (intentionally or otherwise) they have great potential to move, transform and interact with other naturally-occurring substances. ENI research shows that the type of nanomaterial, its coating, size, chemistry and functionality is important in determining the types of change and interaction that occur.

ENI has allowed scientists to work together across borders to understand the complexities associated with nanomaterials, taking a robust, systematic approach that pools strengths and expertise across disciplines. A key output from this has been models that can be used to describe the journey of nanomaterials through the environment and the impacts they might have on environment and human health – models that can be freely used by all.

Many questions remain, such as how the models apply to second- and third-generation nanomaterials, end of life disposal and recovery. However, the research has shown that there are relationships between the materials' physicochemical properties and their effects on organisms in the environment, and that these can be modelled. There is still a pressing need for high-quality data to ensure that these models are applicable to different nanomaterials of different sizes and surface chemistries. Translating these models into specific contexts of use is an ongoing process of knowledge exchange.

There are no plans for a 'third ENI', but NERC and others will continue to support research in this area. NERC recently funded three major projects under its 'Highlight Topics' scheme. These will further investigate nanomaterial transformations, exposure, uptake and effects in freshwater and soil systems; research the environmental fate and toxicology of nanoplastics; and characterise nanomaterials in the environment. Supporting this kind of high-quality, independent research is crucial for hazard and risk assessment, and for the development of robust and useful tools to underpin evidence-based decision-making.

Many of the questions that exist are fundamental scientific ones around nanoparticles' environmental behaviour, transport and biological interactions: these will not necessarily be funded by industry alone. Programmes such as the ENI play a key role in society by signalling the importance we place on this, developing and maintaining an important and necessary set of scientific competencies and independent community of scientists. This can both help us understand more about our natural world and ensure that nanotechnologies are safe and do not pose significant harm to the environment and our health. It can also support the responsible development and long-term sustainability and acceptability of nanotechnologies, both now and in the future.

Publications

Transatlantic Initiative for Nanotechnology and the Environment (TINE)

2015

Barton, L.E., Auffan, M., Durenkamp, M., McGrath, S., Bottero, J-Y. and Wiesner, M.R. (2015) Monte Carlo simulations of the transformation and removal of Ag, TiO_2, and ZnO nanoparticles in wastewater treatment and land application of biosolids. Science of the Total Environment 511: 535-543.

Chen, C., Unrine, J.M., Judy, J.D., Lewis, R.W., Guo, J., McNear, D.H. and Tsyusko, O.V. (2015) Toxicogenomic responses of the model legume *Medicago truncatula* to aged biosolids containing a mixture of nanomaterials (TiO_2, Ag, and ZnO) from a pilot wastewater treatment plant. Environmental Science & Technology 49: 8759-8768.

Dale, A.L., Casman, E.A., Lowry, G.V., Lead, J.R., Viparelli, E. and Baalousha, M. (2015) Modeling nanomaterial environmental fate in aquatic systems. Environmental Science & Technology 49: 2587–2593 *with NanoBEE consortium members*.

Dale, A.L., Lowry, G.V. and Casman, E.A. (2015) Stream dynamics and chemical transformations control the environmental fate of silver and zinc oxide nanoparticles in a watershed-scale model. Environmental Science & Technology 49: 7285–7293.

Dale, A.L., G.V. Lowry, and E. Casman (2015) Much ado about α: Reframing the debate over appropriate fate descriptors in nanoparticle environmental risk modelling. Environmental Science: Nano 2:27-32.

Judy, J.D., McNear Jr., D.H., Chen, C.Lewis, R.W., Tsyusko, O.V., Bertsch, P.M., Rao, W., Stegemeier, J., Lowry, G.V., McGrath, S.P., Durenkamp, M. and Unrine, J.M. (2015) Nanomaterials in biosolids inhibit nodulation, shift microbial community composition, and result in increased metal uptake relative to bulk/dissolved metals. Environmental Science & Technology 49:8751-8758.

Starnes, D. L., Unrine, J. M., Starnes, C. P., Collin, B. E., Oostveen, E. K., Ma, R., Lowry, G.V., Bertsch, P. M. and Tsyusko, O.V (2015) Impact of sulfidation on the bioavailability and toxicity of silver nanoparticles to *Caenorhabditis elegans*. Environmental Pollution 196: 239-246.

Stegemeier, J.P., Schwab, F., Colman, B.P., Webb, S.M., Newville, M., Lanzirotti, A., Winkler, C., Wiesner, M.R. and Lowry, G.V. (2015) Speciation matters: bioavailability of silver and silver sulfide nanoparticles to alfalfa (*Medicago sativa*). Environmental Science & Technology 49: 8451–8460.

Nanomaterial enriched sewage sludge after drying. Cranfield University

2014

Barton, L.E., Auffan, M., Bertrand, M., Barakat, M., Santaella, C., Masion, A., Borschneck, D., Olivi, L., Roche, N., Wiesner, M.R. and Bottero, J.-Y. (2014) Transformation of pristine and citrate-functionalized CeO_2 nanoparticles in a laboratory-scale activated sludge reactor. Environmental Science & Technology 48: 7289-7296.

Barton, L.E., Therezien, M., Auffan, M., Bottero, J.-Y. and Wiesner, M.R (2014) Theory and methodology for determining nanoparticle affinity for heteroaggregation in environmental matrices using batch measurements. Environmental Engineering Science 31: 421-427.

Choi, J., Tsyusko, O.V., Unrine, J.M., Chatterjee, N., Ahn, J.-M., Yang, X., Thornton, B.L., Ryde, I.T., Starnes, D. and Meyer, J.N. (2014) A micro-sized model for the *in vivo* studies of nanoparticle toxicity: what has *Caenorhabditis elegans* taught us? Environmental Chemistry 11: 227-246.

Ma, R., Stegemeier, S., Levard, C., Dale, J.G., Noack, C.W., Yang, T., Brown, G.E. and Lowry, G.V. (2014) Sulfidation of copper oxide nanoparticles and properties of resulting copper sulphide. Environmental Science: Nano 1: 347-357.

Money, E.S., Barton, L.E., Dawson, J., Reckhow, K.H. and Wiesner, M.R. (2014) Validation and sensitivity of the FINE Bayesian network for forecasting aquatic exposure to nano-silver. Science of the Total Environment 473-474: 685-691.

Rathnayake, S., Unrine, J.M., Judy, J., Miller, A.-F., Rao, W. and Bertsch, P.M. (2014) A multitechnique investigation of the pH dependence of phosphate induced transformations of ZnO nanoparticles. Environmental Science & Technology 48: 4757-4764.

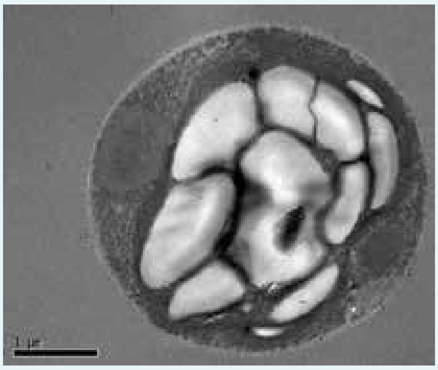
2013

Dale, A.L, Lowry, G.V. and Casman, E.A. (2013) Modelling nanosilver transformations in freshwater sediments. Environmental Science & Technology 47: 12920-12928.

Eduok, S., Martin, B., Villa, R., Nocker, A., Jefferson, B. and Coulon, F. (2013) Evaluation of engineered nanoparticle toxic effect on wastewater microorganisms: Current status and challenges. Ecotoxicology & Environmental Safety 95: 1-9.

Hendren, C.O., Badireddy, A.R., Casman, E. and Wiesner, M.R. (2013) Modelling nanomaterial fate in wastewater treatment: Monte Carlo simulation of silver nanoparticles (nano-Ag). Science of the Total Environment 449: 418–425.

Levard, C., Hotze, E.M., Colman, B.P., Dale, A.L., Truong, L., Yang, X.Y., Bone, A.J., Brown Jr., G.E., Tanguay, R.L., Di Giulio, R.T., Bernhardt, E.S., Meyer, J.N., Wiesner, M.R. and Lowry, G.V. (2013) Sulfidation of silver nanoparticles: natural antidote to their toxicity. Environmental Science & Technology 47: 13440-13448.



Transmission electron micrograph of C. vulgaris.
Heriot-Watt University

Ma, R., Levard, C., Judy, J.D., Unrine, J.M., Durenkamp, M., Martin, B., Jefferson, B., Lowry, G.V. (2013) Fate of zinc oxide and silver nanoparticles in a pilot wastewater treatment plant and in processed biosolids. Environmental Science & Technology, 48: 104-112.

Ma, R., Levard, C., Michel, F.M., Brown Jr, G.E. and Lowry, G.V. (2013) Sulfidation mechanism for zinc oxide nanoparticles and the effect of sulfidation on their solubility. Environmental Science & Technology 47:2527–2534.

Whitley, A.R., Levard, C., Oostveen, E., Bertsch, P.M., Matocha, C.J., Von der Kammer, F. and Unrine, J.M. (2013) Behaviour of Ag nanoparticles in soil: Effects of particle surface coating, aging and sewage sludge amendment. Environmental Pollution 182: 141-149.

2012

Handy, R.D., Cornelis, G., Fernandes, T., Tsyusko, O., Decho, A., Sabo-Attwood, T., Metcalffe, C., Steevens, J.A., Klaine, S.J., Koelmans, A.A. and Horne, N. (2012) Ecotoxicity test methods for engineered nanomaterials: practical experiences and recommendations from the bench. Environmental Toxicology & Chemistry 31: 15–31.

Judy, J.D., Tollamadugu, N.V.K.V.P. and Bertsch, P.M. (2012) Pin oak (Quercus palustris) leaf extract mediated synthesis of triangular, polyhedral and spherical gold nanoparticles. Advances in Nanoparticles 1: 79-85.

Judy, J.D., Unrine, J.M., Rao, W. and Bertsch, P.M. (2012) Bioaccumulation of gold nanomaterials by *Manduca sexta* through dietary uptake of surface contaminated plant tissue. Environmental Science & Technology 46: 12672-12678.

Judy, J.D., Unrine, J.M., Rao, W., Wirick, S. and Bertsch, P.M. (2012) Bioavailability of gold nanomaterials to plants: importance of particle size and surface coating. Environmental Science & Technology 46: 8467–8474.

Lowry, G.V., Espinasse, B.P., Badireddy, A.R., Richardson, C.J., Reinsch, B.C., Bryant, L.D., Bone, A.J., Deonarine, A., Chae, S., Therezien, M., Colman, B.P., Hsu-Kim, H., Bernhardt, E.S., Matson, C.W. and Wiesner, M.R. (2012) Long-term transformation and fate of manufactured Ag nanoparticles in a simulated large scale freshwater emergent wetland. Environmental Science & Technology 46: 7027-7036.

Money, E. S., Reckhow, K.H. and Wiesner, M.R. (2012) The use of Bayesian networks for nanoparticle risk forecasting: Model formulation and baseline evaluation. Science of the Total Environment 426: 436-445.

Neal, A.L., Kabengi, N., Grider, A. and Bertsch, P.M. (2012) Can the soil bacterium *Cupriavidus necator* sense ZnO nanomaterials and aqueous Zn^{2+} differentially? Nanotoxicology, 6: 371-380.

Tsyusko, O.V., Hardas, S.S., Shoults-Wilson, W.A., Starnes, C.P., Joice, G., Butterfield, D.A and Unrine, J.M. (2012) Short-term molecular-level effects of silver nanoparticle exposure on the earthworm, *Eisenia fetida*. Environmental Pollution 171: 249-255.

Tsyusko, O.V., Unrine, J.M., Spurgeon, D., Blalock, E., Starnes, D., Tseng, M., Joice, G. and Bertsch, P.M. (2012) Toxicogenomic responses of the model organism *Caenorhabditis elegans* to gold nanoparticles. Environmental Science & Technology 46: 4115-4124.

Von der Kammer, F., Ferguson, P.L., Holden, P.A., Masion, A., Rogers, K.R., Klaine, S.J., Koelmans, A.A., Horne, N. and Unrine, J.M. (2012) Analysis of engineered nanomaterials in complex matrices (environment and biota): General considerations and conceptual case studies. Environmental Toxicology & Chemistry 31: 32-49.

2011

Judy, J.D., Unrine, J.M. and Bertsch, P.M. (2011) Evidence for biomagnification of gold nanoparticles within a terrestrial food chain. Environmental Science & Technology 45: 776-781.

Consortium for Manufactured Nanomaterial Bioavailability and Environmental Exposure (NanoBee)

2015

Arkill, K.P., Mantell, J.M., Plant, S.R., Verkade, P. and Palmer, R.E. (2015) Using size-selected gold clusters on graphene oxide films to aid cryo-transmission electron tomography alignment. Scientific Reports 5: 9234.

Baalousha, M., Arkill, K.P., Romer, I., Palmer, R.E. and Lead, J.R. (2015) Transformations of citrate and Tween coated silver nanoparticles reacted with Na_2S. Science of the Total Environment 502: 344-353.

Cross, R, Tyler CR, and Gallloway, T.G. (2015) Transformations that affect fate, form and bioavailability of inorganic nanoparticles in aquatic sediments. Environmental Chemistry 12: 627-642.

Goodhead, R.M., Moger, J, Galloway, T.S., and Tyler, C.R (2015) Tracing engineered nanomaterials in biological tissues using coherent anti-Stokes Raman scattering (CARS) microscopy - A critical review. Nanotoxicology. 11:1-12.

Jennings, V., Goodhead, R., and Tyler, C.R. (2015) Ecotoxicology of nanomaterials in aquatic systems. In: Baalousha, M., and Lead, J.R (eds) Frontiers of Nanoscience – Volume 8. Oxford: Elsevier, pp.3-20.

Kalman, J., Paul, K.B., Khan, F.R., Stone, V., Fernandes, T.F. (2015) Characterisation of bioaccumulation dynamics of three differently coated silver nanoparticles and aqueous silver in a simple freshwater food chain. Environmental Chemistry 12: 662-672.

Khan, R.P., Paul, K.B., Dybowska, A., Valsami-Jones, E., Lead, J.R., Stone, V. and Fernandes, T. (2015) Accumulation dynamics and acute toxicity of silver nanoparticles to *Daphnia magna* and *Lumbriculus variegatus:* implications for metal modelling approaches. Environmental Science & Technology 49: 4389-4397.

Stoiber, T., Croteau, M-N., Romer, I, Tejamaya, M., Lead, J.R. and Luoma, S.N. (2015) Influence of hardness on the bioavailability of silver to a freshwater snail after waterborne exposure to silver nitrate and silver nanoparticles. Nanotoxicology 9: 918-927.

Wray, A.T. and Klaine, S.J. (2015) Modelling the influence of physicochemical properties on gold nanoparticle uptake and elimination by *Daphnia magna*. Environmental Toxicology & Chemistry 34: 860-872.

2014

Collin, B., Auffan, M., Johnson, A.C., Kaur, I., Keller, A.A., Lazareva, A., Lead, J.R., Ma, X., Merrifield, R.C., Svendsen, C., White, J. and Unrine, J.M. (2014) Environmental release, fate and ecotoxicological effects of manufactured ceria nanomaterials. Environmental Science: Nano 1: 533-548 *with TINE consortium members.*

Croteau, M-N., Dybowska, A.D., Luoma, S.N., Misra, S.K. and Valsami-Jones, E. (2014) Isotopically modified silver nanoparticles to assess nanosilver bioavailability and toxicity at environmentally relevant exposures. Environmental Chemistry 11: 247-256.

Croteau, M-N., Misra, S.K., Luoma, S.N. and Valsami-Jones, E. (2014) Bioaccumulation and toxicity of CuO nanoparticles by a freshwater invertebrate after waterborne and dietborne exposures. Environmental Science & Technology 48: 10929-10937.

Edgington, A.J., Petersen, E.J., Herzing, A.A., Podila, R., Rao, A. and Klaine, S.J. (2014) Microscopic investigation of single-wall carbon nanotube uptake by *Daphnia magna.* Nanotoxicology 8: 2-10.

Luoma, S.N., Khan, F.R. and Croteau, M.-N. (2014) Bioavailability and bioaccumulation of metal-based engineered nanomaterials in aquatic environments: concepts and processes. In: Lead, J.R. and Valsami-Jones, E. (eds) Frontiers of Nanoscience – Volume 7, Oxford: Elsevier pp.157-193.

2013

Merrifield, R.C., Wang, Z.W., Palmer, R.E. and Lead, J.R. (2013) Synthesis and characterization of polyvinylpyrrolidone coated cerium oxide nanoparticles. Environmental Science & Technology 47: 12426-12433.

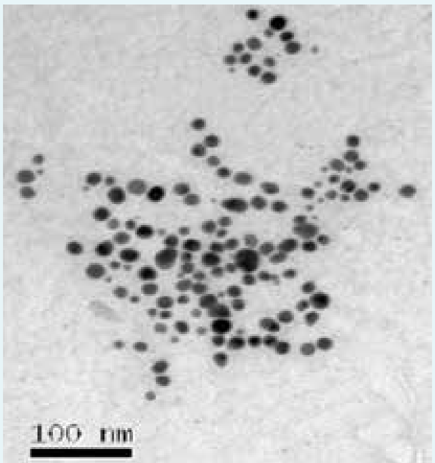
Newton, K.M., Puppala, H.L., Kitchens, C.L., Colvin, V.L., and Klaine, S.J. (2013) Silver nanoparticle toxicity to *Daphnia magna* is a function of dissolved silver concentration. Environmental Toxicology & Chemistry 32: 2356-2364.

Osborne, O., Johnston, B.D., Cole, P., Moger, J., Kudoh, T., Lead, J.R., and Tyler, C.R. (2013) Effect of particle size and coating on nanoscale Ag and TiO_2 exposure in zebrafish embryos. Nanotoxicology 7: 1315-1324.

Romer, I., Gavin, A.J., White, T.A., Merrifield, R.C., Chipman, J.K., Viant, M.R. and Lead, J.R. (2013) The critical importance of defined media conditions in *Daphnia magna* nanotoxicity studies. Toxicology Letters 223: 103-108.

Van Aerle, R., Lange, A., Moorhouse, A., Paszkiewicz, K.H., Ball, K., Johnston, B., deBastos, E., Booth, T., Tyler, C.R., and Santos, E (2013) Molecular mechanisms of silver nanoparticle toxicity in zebrafish embryos. Environmental Science & Technology 47: 8005-8014.

Wang J., Koo, Y. , Alexander, A., Yang, Y., Westerhof, S., Zhang, Q., Schnoor, J.L., Colvin, V., Braam, J., and Alvarez, P.J.J. (2013) Phyto-stimulation of poplars and *Arabidopsis* exposed to silver nanoparticles and Ag^+ at sub-lethal concentrations. Environmental Science & Technology 47: 5442–5449.



Transition electron micrograph of pristine PVP-silver nanoparticles. University of Birmingham

Yang Y., Wang, J., Zhu, H., Colvin, V.L. and Alvarez, P.J.J (2013) Impacts of silver nanoparticles on cellular and transcriptional activity of nitrogen cycling bacteria. Environmental Toxicology & Chemistry 32: 1488–1494.

Yang, Y., Quensen, J., Mathieu, J., Wang, Q., Wang, J., Li, M., Tiedje, J.M. and Alvarez, P.J.J. (2013) Pyrosequencing reveals higher impact of silver nanoparticles than Ag^+ on the microbial community structure of activated sludge. Water Research 48:317-25.

2012

Baalousha, M., Ju-Nam, Y., Cole, P.A., Gaiser, B., Fernandes, T.F., Hriljac, J.A., Jepson, M.A., Stone, V., Tyler, C.R. and Lead, J.R. (2012) Characterization of cerium oxide nanoparticles – Part 1: size measurements. Environmental Toxicology & Chemistry 31: 983-993.

Baalousha, M., Ju-Nam, Y., Cole, P.A., Hriljac, J.A., Jones, I.P., Tyler, C.R., Stone, V., Fernandes, T.F., Jepson, M.A. and Lead, J.R. (2012) Characterization of cerium oxide nanoparticles – Part 2: nonsize measurements. Environmental Toxicology & Chemistry 31: 994-1003.

Fabrega, J., Tantra, R., Amer, A., Stolpe, B., Tomkins, J., Fry, T., Lead, J.R., Tyler, C.R. and Galloway, T.S. (2012) Sequestration of zinc from zinc oxide nanoparticles and life cycle effects in the sediment dweller amphipod *Corophium volutator.* Environmental Science & Technology 46: 1128-1135.

Handy, R.D., Cornelis, G., Fernandes, T., Tsyusko, O., Decho, A., Sabo-Attwood, T., Metcalffe, C., Steevens, J.A., Klaine, S.J., Koelmans, A.A. and Horne, N. (2012) Ecotoxicity test methods for engineered nanomaterials: practical experiences and recommendations from the bench. Environmental Toxicology & Chemistry 31: 15–31.

Handy, R.D., van den Brink, N., Chappell, M., Mühling, M., Behra, R., Dušinská, M., Simpson, P., Ahtiainen, J., Jha, A.N., Seiter, J., Bednar, A., Kennedy, A., Fernandes, T.F., and Riediker, M. (2012) Practical considerations for conducting ecotoxicity test methods with manufactured nanomaterials: what have we learnt so far? Ecotoxicology 21: 933-972.

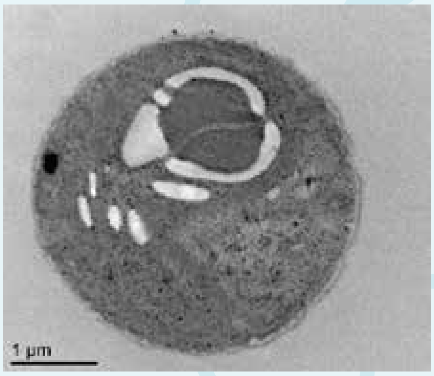
Lange, A., Katsu, Y., Miyagawa, S., Ogino, Y., Urushitani, H., Kobayashi, T., Hirai, T., Shears, J.A., Nagae, M., Yamamoto, Ohnishi, Y., Oka, T., Tatarazako, N., Ohta, Y., Tyler, C.R. and Iguchi, T. (2012) Comparative responsiveness to natural and synthetic estrogens of fish species commonly used in the laboratory and field monitoring. Aquatic Toxicology 109: 250-258.

Larner, F., Dogra, Y., Dybowska, A., Fabrega, J., Stolpe, B., Bridgestock, L.J., Goodhead, R., Weiss, D.J., Moger, J., Lead, J.R., Valsami-Jones, E., Tyler, C.R., Galloway, T.S. and Rehkämper, M. (2012) Tracing bioavailability of ZnO nanoparticles using stable isotope labelling. Environmental Science & Technology 46: 12137-12145.

Lowry, G.V., Gregory, K.B., Apte, S.C. and Lead, J.R. (2012) Transformations of nanomaterials in the environment. Environmental Science & Technology 446: 6893-6899 *with TINE consortium members.*

Misra, S.K., Dybowska, A., Berhanu, D., Luoma, S.N., Valsami-Jones, E. (2012) The complexity of nanoparticle dissolution and its importance in nanotoxicological studies. Science of the Total Environment 438: 225-232.

Tejamaya, M., Römer, I., Merrifield, R.C. and Lead, J.R. (2012) Stability or citrate, PVP, and PEG coated silver nanoparticles in ecotoxicology media. Environmental Science & Technology 46: 7011-7017.



Transmission electron micrograph of C. vulgaris *after exposure to citrate-coated silver nanoparticles for 72 hours.*
Heriot-Watt University

Xiu, Z., Zhang, Q., Puppala, H.L., Colvin, V.L., and Alvarez, P.J.J. (2012). Negligible particle-specific antibacterial activity of silver nanoparticles. Nanoletters 12: 4271−4275.

2011

Fabrega, J., Luoma, S.N., Tyler, C.R., Galloway, T.S. and Lead, J.R. (2011) Silver nanoparticles: Behaviour and effects in the aquatic environment. Environment International 37: 517-531.

Xiu, Z-M., Ma, J. and Alvarez, P.J.J. (2011) Differential effect of common ligand and molecular oxygen on antimicrobial activity of silver nanoparticles versus silver ions. Environmental Science & Technology 45: 9003-9008.

Risk Assessment for Manufactured Nanoparticles Used in Consumer Products (RAMNUC)

2015

Chen, S., Goode, A.E., Skepper, J.N., Thorley, A.J., Seiffert, J.M., Chung, K.F., Tetley, T.D., Shaffer, M.S.P., Ryan, M.P., and Porter, A.E. (2015) Avoiding artefacts during electron microscopy of silver nanomaterials exposed to biological environments. Journal of Microscopy doi: 10.1111/jmi.12215

Loez-Heras, M., Theodorou, I.G., Leo, B.F., Ryan, M.P. and Porter, A.E. (2015) Towards understanding the antibacterial activity of Ag nanoparticles: electron microscopy in the analysis of the materials-biology interface in the lung. Environmental Science: Nano 2: 312-326.

Seiffert, J., Hussain, F., Wiegman, C., Li, F., Bey, L., Baker, W., Porter, A., Ryan, M.P., Chang, Y., Gow, A., Zhang, J., Zhu, J., Tetley, T.D. and Chung, K.F. (2015) Pulmonary toxicity of instilled silver nanoparticles: influence of size, coating and rat strain. PLoS ONE 10: e0119726. doi: 10.1116/1.4926547.

Theodorou, I.G., Botelho, D., Schwander, S., Zhang, J., Chung, K.F., Tetley, T.D., Shaffer, M.S., Gow, A., Ryan, M.P. and Porter, A.E. (2015) Static and dynamic microscopy of the chemical stability and aggregation state of silver nanowires in components of murine pulmonary surfactant. Environmental Science & Technology 49: 8048-56.

2014

Royce, S.G., Mukherjee, D., Cai, T., Xu, S.S., Alexander, J.A., Mi, Z., Calderon, L., Mainelis, G., Lee, K., Lioy, P.J., Tetley, T.D., Chung, K.F. and Zhang, J., and Georgopoulos, P.G. (2014) Modelling population exposures to silver nanoparticles present in consumer products. Journal of Nanoparticle Research 16: 2724 - 2749.

Sarkar, S., Zhang, L., Subramaniam, P., Lee, K.-B., Garfunkel, E., Strickland, P.A.O., Mainelis, G., Lioy, P.J., Tetley, T.D., Chung, K.F., Zhang, J., Ryan, M., Porter, A., and Schwander, S. (2014) Variability in bioreactivity linked to changes in size and zeta potential of diesel exhaust particles in human immune cells. PLOS ONE 9: e97304. doi:10.1371/journal.pone.0097304.

Theodorou, I.G., Ryan, M.P., Tetley, T.D. and Porter, A.E. (2014) Inhalation of silver nanomaterials--seeing the risks. International Journal of Molecular Sciences 15:23974.

2013

Chen, S., Goode, A.E., Sweeney, S., Theodorou, I.G., Thorley, A.J., Ruenraroengsak, P., Chang, Y., Gow, A., Schwander, S., Skepper, J., Zhang, J.J., Shaffer, M.S., Chung, K.F., Tetley, T.D., Ryan, M.P. and Porter, A.E. (2013) Sulfidation of silver nanowires inside human alveolar epithelial cells: a potential detoxification mechanism. Nanoscale 5: 9839-47.

Chen, S., Theodorou, I.G., Goode, A.E., Gow, A., Schwander, S., Zhang, J.J., Chung, K.F., Tetley, T.D., Shaffer, M.S., Ryan, M.P., and Porter, A.E. (2013) High-resolution analytical electron microscopy reveals cell culture media-induced changes to the chemistry of silver nanowires, Environmental Science & Technology 47: 13813-13821.

Fen, L.B., Chen, S., Kyo, Y., Herpoldt, K-L., Terrill, N.J., Dunlop, I.E., McPhail, D.S., Shaffer, M.S., Schwander, S., Gow, A., Zhang, J., Chung, K.F, Tetley, T.D., Porter, A.E and Ryan, M.P. (2013) The stability of silver nanoparticles in a model of pulmonary surfactant. Environmental Science & Technology 47: 11232-11240.

Leo, B.F., Chen, S., Kyo, Y., Herpoldt, K.-L., Terrill, N.J., Dunlop, I.E., McPhail, D.S., Shaffer, M.S., Schwander, S., Gow, A., Zhang, J., Chung, K.F., Tetley, T.D., Porter, A.E., and Ryan, M.P. (2013). The stability of silver nanoparticles in a model of pulmonary surfactant, Environmental Science & Technology 47: 11232-11240.

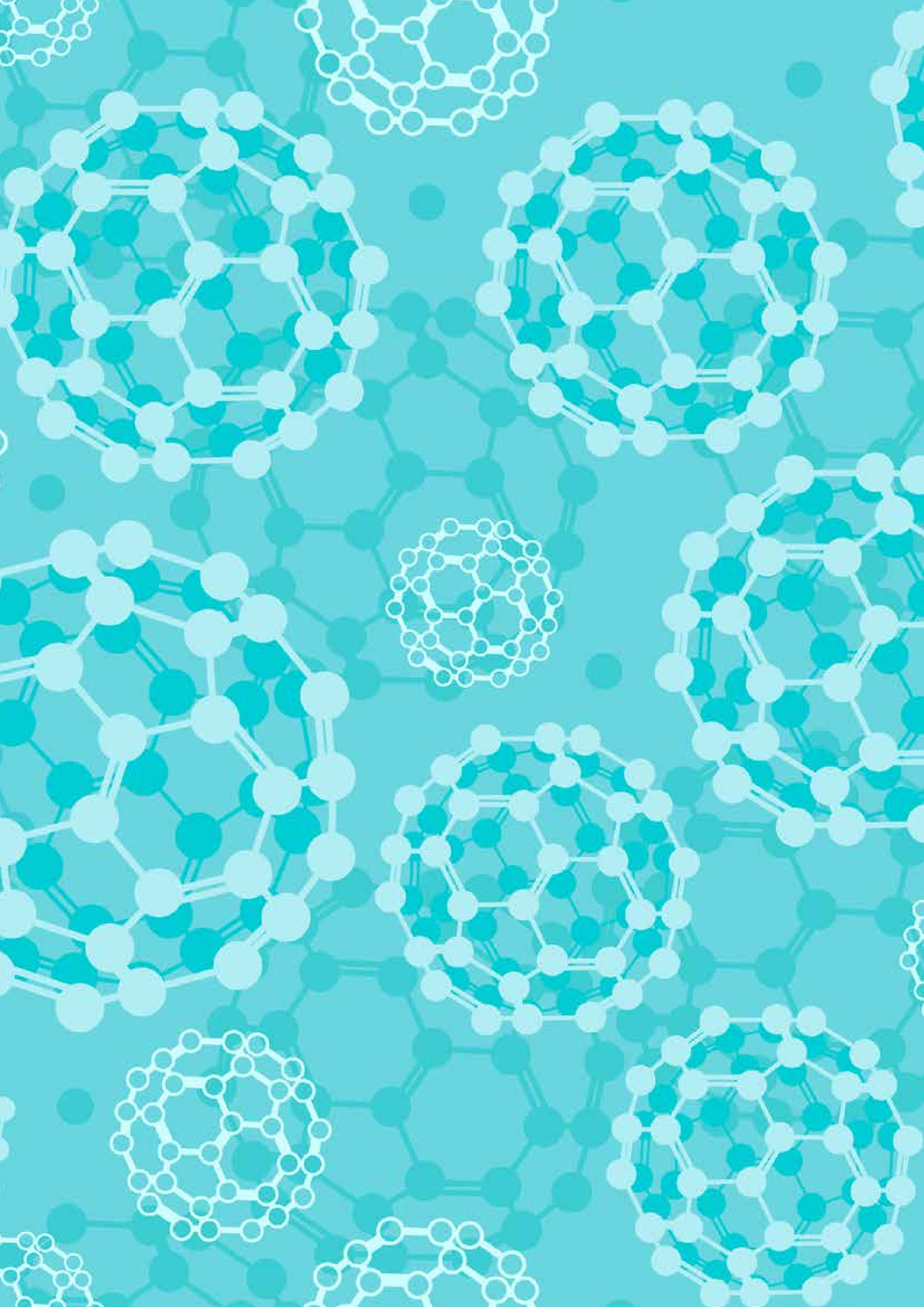
Nazarenko, Y., Zhen, H., Han, T., Lioy, P.J., and Mainelis, G. (2013) Potential for Inhalation exposure to engineered nanoparticles from nanotechnology-based cosmetic powders. Environmental Health Perspectives 120: 885-892.

Subramanium, P., Lee, S.J., Shah, S., Patel, S., Starovoytov, V., and Lee, K-B. (2013) Generation of a library of non-toxic quantum dots for cellular imaging and SiRNA delivery. Advanced Materials 24: 4014-4019.

Zhang, J., Nazarenko, Y., Zhang, L., Calderon, L., Lee, K-B. Garfunkel, E., Schwander, S., Tetley, T.D., Chung, K.F., Porter, A.E., Ryan, M., Lioy, P.J. and Mainelis, G. (2013) Impact of nanosized ceria additive on diesel engine emissions of particulate and gaseous pollutants. Environmental Science & Technology 47: 13077-13085.

2012

Nazarenko, Y., Zhen, H., Han, T., Lioy, P. and Mainelis, G. (2012) Nanomaterial inhalation exposure from nanotechnology-based cosmetic powders: a quantitative assessment. Nanoparticle Research 14: 1229-1243.



Environmental
Nanoscience Initiative

More information
www.nerc.ac.uk/research/programmes/nanoscience/

Programme Coordinator
Professor Richard Owen
University of Exeter
Email: r.j,owen@exeter.ac.uk

Knowledge Exchange Fellow (ENI Programme)
Dr Sophie Rocks
Cranfield University
Email: s.rocks@cranfield.ac.uk