EMERGING CHALLENGES

Nanotechnology and the environment

Source: Donna Sheppard/ Light up the World Foundation

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Nanotechnology and the environment

Nanotechnology has enormous potential for social, economic, and environmental benefits—from innovative medical techniques to savings on materials and energy, as well as advances in detection and remediation of pollution. However, with environmental impacts as yet largely unknown and public controls largely absent, more systematic research and sector-specific policies are necessary.

INTRODUCTION

Nanotechnology is a field of applied science concerned with the control of matter at dimensions of roughly 1 to 100 nanometres—one nanometre is one-billionth of a metre **(Box 1)**. The appeal of nanoparticles is that they can be engineered to function in ways that naturally occurring materials do not. Their large surface area per unit volume and enhanced chemical reactivity can be exploited in novel applications.

Reseacrhers in nanotechnology anticipate that it will have profound effects on industry and technology, human health, social and economic development, and the environment. Public and private investments in nanotechnology are significant and increasing because of its potential to transform sectors as diverse as medicine, manufacturing, energy, water supply, and transportation.

Nanotechnology is poised to become a major element in the global economy. In 2004, nanotech products accounted for less than 0.1 per cent of revenue from manufacturing. By 2014 they are projected to account for 14 per cent, totaling US$ 2.6 trillion—a figure that will match the information technology and telecommunication industries combined (Lux Research 2004).

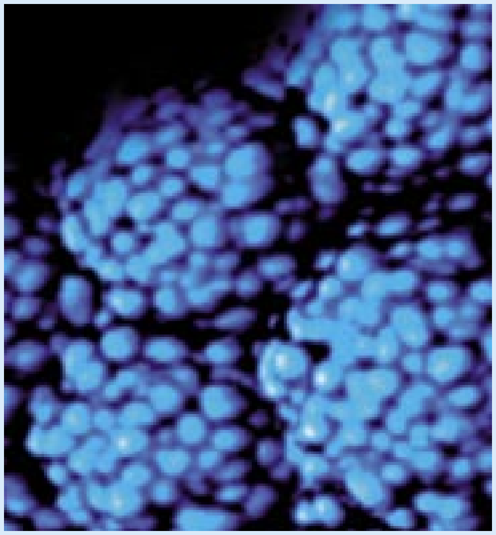
Currently the private sector funds about half the research expenditures in nanotechnology. To date, the majority of nanotechnology research is being carried out by countries belonging to the Organization for Economic Co-operation and Development (OECD). However, a growing number of emerging economies such as Brazil and Thailand are making it a priority (Millennium Project 2005).

As with most new and evolving technologies, there is a great deal of emphasis on the potential benefits of nanotechnology, but much less is known about the potential for harm. In 2005, more than US$10 billion was spent on nanotech research **(Figure 1)**. Yet the United States and European Union were estimated to be spending only US$39 million per year on research on the effects of nanoparticles on human health and the environment (Service 2005).

It is essential to correct this imbalance by directing more resources to investigating the impacts of nanomaterials, minimizing the health and environmental risks, and supporting sustainable development.

Although it may be appropriate to approach the subject of nanotechnology and the environment with enthusiasm, policy makers need to develop science-

Box 1: Defining features of nanotechnology



Nanotechnology is a generic and evolving term that encompasses the development of a wide range of materials and products. Definitions vary, but the essential characteristic is the deliberate exploitation of particles or structures that are measured on the nanometre (nm) scale.

A nanometre is one-billionth of a metre; by comparison, a human hair is 80 000 nm thick. There are three types of nanoparticles:

- **Natural** (such as tiny particles generated from volcanic eruptions),
- **Incidental** (such as emissions from engine combustion), and
- **Engineered** (purposely manufactured).

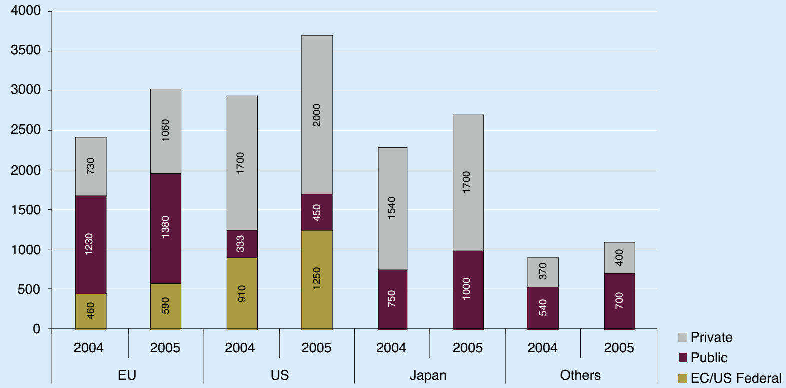
Nanoparticles may be divided into soluble and insoluble, the latter being of greater potential toxicological concern when released.

Engineered nanoparticles are usually developed by scaling commonly used materials (e.g., carbon, metal oxides, and precious metals) from large particles to small. Others are built atom-by-atom to create completely new compounds that have no large-size counterpart. Some are 'fixed' (embedded in materials); others are 'free' and could be released into the environment.

Due to nanotechnology, researchers are developing new materials with extraordinary characteristics. Many materials combine the advantages of inorganic nanoparticles (hardness and breathability) and organic polymer particles (elasticity and water repellency). One example is a new generation of 'binders' developed by BASF, known by the brandname COL9TM. When included in exterior paints, these binders provide extreme durability; resistance to soiling, chalking and cracking; and color tone stability.

Source: BASF Aktiengesellschaft

Figure 1: Research & Technological Development Expenditures (in millions of US dollars)



Sources: European Commission (2005) and Lux Research (2006).

based frameworks to manage the uncertainties and risks. Increased international cooperation is also needed to address transboundary issues involving the development and use of nanomaterials and products. Several international initiatives are being undertaken including the Global Dialogue on Nanotechnology and the Poor: Opportunities and Risks, the International Risks Governance Council, and the International Council for Nanotechnology. Additional support programmes are sponsored by the European Commission, the USA, and other authorities (Box 2).

THE ENVIRONMENTAL BENEFITS OF NANOTECHNOLOGY

Nanoparticles have the potential to deliver environmental benefits both in production processes and in products. Nanomaterials can substitute for conventional materials that require more raw material, are more energy-intensive to produce, or are known to be environmentally harmful (Masciangioli and Zhang 2003). New nanotechnologies seem poised to enhance environmental protection and improve pollution detection and remediation.

A growing number of nanoparticles are 'functionalized', meaning that their surfaces are designed to trigger specific chemical or biological reactions (Table 1). This offers novel mechanisms for targeted delivery of drugs in humans and animals or of pesticides and fertilizers for crops. Targeted delivery facilitates more effective use of substances in far lower amounts—it has potential to reduce use of chemicals and materials, particularly those with negative environmental impacts such as pesticides.

Improved monitoring

One way in which advances in nanotechnology may benefit the environment (both indoor and outdoor) is through detection devices that are less expensive and more sensitive—in some cases thousands or millions of times more sensitive—than existing devices. For example, new protein-based nanotech sensors can detect mercury at concentrations of approximately one part in 10^{-15} or one-quadrillionth, a task previously impossible (Bontidean 1998). Using nanoparticles of europium oxide, a highly sensitive method has been developed to measure the pesticide atrazine, a frequent groundwater contaminant (Feng and others 2003).

Table 1: Nanomaterials 'made-to-order'

The ability to manipulate nanoparticles allows scientists to fine-tune the properties of materials so the resulting product serves specific purposes.

Properties	Examples
Chemical	Higher surface-to-volume ratio makes particles highly reactive, increasing their efficiency as catalysts for desired chemical reactions.
Electrical	Increased electrical conductivity in ceramics and magnetic nanocomposites, increased electrical resistance in metals
Mechanical	Improved hardness and toughness of metals and alloys, ductility and superplasticity of ceramics.
Optical	Increased conversion efficiency of light to electrical charge in photoelectronic devices such as solar panels
Sterical	The spatial arrangement of atoms in a substance affects chemical reactions and facilitates increased selectivity. For example, hollow spheres can be used to tranport and control the release of specific drugs.
Biological	Increased permeability through biological barriers (membranes, blood-brain barrier, etc.), improved biocompatibility (i.e., the quality of NOT having toxic or injurious effects on biological systems).

Source: Luther, 2004.

Box 2: Nanotechnology and the UN Millennium Development Goals

Children in Sri Lanka display 0.1-watt white LED bulbs, produced using nanolayers of semi-conductor material on a sapphire substrate. This technology is transforming daily life in some of the world's poorest and most remote villages. It may be possible to light entire villages with less energy than a standard 100-watt bulb.

Source: Light Up The World Foundation/University of Moratuwa

Nanotechnology has the potential to contribute to the targets set for achieving the UN Millennium Development Goals, particularly in the areas of affordable energy, clean water,human health, and the environment.

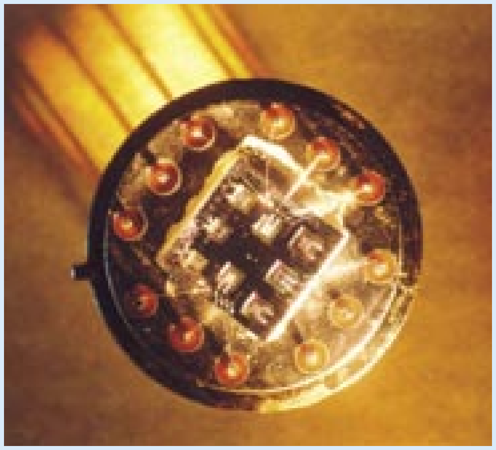
Various nanotechnologies show promise for providing cleaner, more affordable, and more efficient ways to harness renewable energy. This can help to reduce dependency on conventional energy sources and support greater energy self-sufficiency, an important goal for developing nations.

Nanofiltration may improve access to safe and affordable drinking water and basic sanitation, with direct implications for sanitation and public health.

To bring these promises to fruition, public research programmes have an important role to play in providing greater incentives and encouragement for nanotechnologies that support sustainable development.

Sources: Hillie and others 2006, Global Dialogue on Nanotechnology and the Poor 2006, Zhang 2003, Yavuz and others 2006, Yean and others 2005

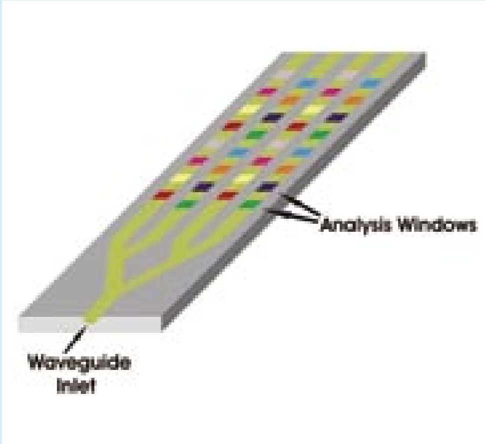
Box 3: Environmental monitoring with nanotechnology



Monitoring Air Pollution Hot Spots

Thin layers of nanocrystalline metal oxide are the key component of solid-state gas sensors for air quality monitoring.

Source: Instituto de Fisica Aplicada, CISC Madrid



Detecting Water Contaminants

Water enters the waveguide inlet and passes over biochemical sensors, making it possible to simultaneously test for more than 30 contaminants.

Source: Eberhard-Karls-University Tuebingen, Institute of Physical and Theoretical Chemistry

Nanotechnology can be used to improve monitoring of air and water quality. For example, miniaturized air quality monitoring devices selectively detect carbon monoxide (CO) and nitrogen dioxide (NO_2) by measuring changes in electrical conductivity that occur when these gas molecules are present on the surface. Other gases such as methane, ozone, and benzene can also be detected.

In some applications, nano-based sensors outperform conventional air pollution monitoring devices (left-hand image, above). They provide faster response with real-time analytical capability, greatly improved geographical resolution, simplified operation, and lower running costs. They are ideal for monitoring localized pollution peaks in urban areas.

To verify the safety of drinking water, it is necessary to monitor pollutants (pesticides, antibiotics, natural toxins, carcinogens, industrial waste, etc.) down to the level of one nanogram (i.e., one-billionth of a gram) per litre. A new biochemical sensor uses an integrated optical chip to analyze water from various sources by means of a miniaturized immunoassay system (right-hand image, above). In approximately 20 minutes, the sensor can detect and provide data on more than 30 different substances. The device can be re-used up to 500 times before the surface chemistry needs to be regenerated.

Sources: Rickerby and others 2000, Comini and others 2001, Graf and others 2004, Tschmelak and others 2005, Proll and others 2005, Hua and others 2005

Box 4: Windows that save energy

Windows are inefficient from an energy standpoint. In hot seasons, sun shining through glass increases indoor temperatures and the need for cooling. In cool seasons, windows leak a significant portion of the indoor heat, wasting heating energy. Depending on the country, a significant amount of energy may be used to heat or cool buildings.

Nanoscale window coatings show promise for reducing energy consumption and CO_2 emissions. Coatings tailored to warm climates allow visible light to pass through glass but block infrared wavelengths. In cool climates, coatings make more efficient use of light and heat by hindering their radiation back to the outside world. Other coatings still in development can respond to changes in the weather or the angle of the light.

At present, reflective coatings are expensive to produce. Although they are less effective, so-called 'absorptive coatings' provide a more affordable alternative. A coating that contains nanoparticles of the compound lanthanum hexaboride (LaB_6) is already on the market and is used to make more cost-effective solar glazing.

Sources: Muir 2004, Schelm 2003

Many new nanotechnology-based monitoring devices operate on site and in real-time, simultaneously measuring a broad range of pollutants and toxic agents. Rapid detection allows for swift response, thereby minimizing damage and reducing remediation costs (Box 3).

Remediating pollution

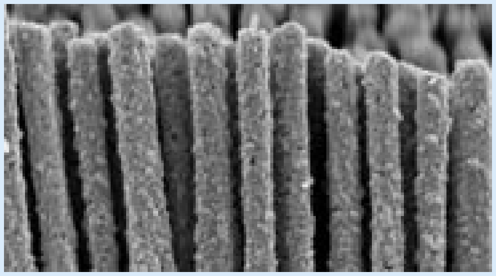
Nanotechnology-based solutions may also help reduce or prevent pollution and toxic emissions at source. Nanostructured catalysts based on metal oxides or metal nanoparticles show promise in reducing industrial and vehicle emissions (Rickerby and Morrison 2006). For example, a variety of precious metal nanoparticles have the ability to oxidize poisonous carbon monoxide (CO) in vehicle exhausts, transforming them into less harmful carbon dioxide (CO_2).

At the nanoscale, various particles demonstrate impressive capabilities to remediate pollutants. Nanoparticles of titanium dioxide (TiO_2) absorb energy from light and then oxidize nearby organic molecules; this property of photocatalysis is exploited to make coatings that attract and oxidize pollutants, such as vehicle and industrial emissions (Strini and others 2005). These properties can be exploited to create self-cleaning surfaces (e.g., self-cleaning glass or walls that can trap particles of air pollution).

Wood coated with a nanoparticle surface becomes extremely water repellant or 'superhydrophobic.' Surfaces treated in this way become self-cleaning and require little maintenance.

Source: BASF Aktiengesellschaft

Box 5: Nanotechnology and better energy options



Scanning electron microscope image of the nanostructured electrode architecture used in an advanced lithium ion battery. The individual columns are approximately 200 nanometres in diameter.

Source: Université de Picardie Jules Verne, Amiens

Lithium batteries increase safety and last longer

The power output of rechargeable lithium batteries can be increased by 50 per cent by using nanostructured electrodes containing lithium cobalt oxide. These batteries are intrinsically safer: they have faster charge/discharge rates and better accommodate the expansion caused by migrating lithium ions during charging. Lithium batteries are already being used to power a wide range of devices, many of which operate in remote locations and extreme environments – from oceans to outer space.

Nanomaterials are improving the efficiency of existing solar energy technologies.

Source: Audio Visual Library of the European Commission

Nanomaterials trap and transform solar energy

Various nanomaterials such as nanostructured cadmium and copper indium diselenide are proving effective in solar energy technologies, including photovoltaic cells. Thin layers of semiconductor materials can be applied to inexpensive bases, such as glass, plastic, or metal, to create photovoltaic cells. Compared to conventional silicon solar cells, less semiconductor material is required and manufacturing costs are significantly reduced.

New vehicles powered by hydrogen fuel produce zero green-house gas emissions. Nanotechnology can facilitate hydrogen gas storage.

Source: Daimler-Chrylser

Better storage for emission-free fuels

New vehicles in development operate by converting hydrogen fuel into electrical energy, producing water as a byproduct. Thus, they offer the promise of eliminating greenhouse gas emissions in the transportation sector. However, hydrogen gas is highly flammable and presents considerable storage and transport problems. Nanomaterials that facilitate storage include metal hydrides (chemical compounds formed when hydrogen gas interacts with metals). Some metal hydrides react at near room temperature and at pressures only a few times greater than that of the Earth's atmosphere, making them suitable candidates for hydrogen storage. However, they have relatively slow absorption and desorption rates. Nanostructured materials can reduce this problem by providing fast diffusion paths for hydrogen.

Sources: Baughman and others 2002, Oelerich and others 2001, Rosi and others 2003, Poizot and others 2000, Tarascon and Armand 2001,Bruce and others 2005, Stalmans and others 1998, Pizzini and others 2005

New nanomaterials are being developed that can bind pollutants and then be mopped up, much as one uses a sponge to mop up spilled water. This might be particularly useful, for example, in countries such as Bangladesh where arsenic in groundwater is at levels above safety limits set by the World Health Organization and is responsible for various health problems.

Source: Still Pictures

Several nanostructured materials show promise for cleaning water and groundwater. Nanoporous membranes that filter pathogens and other undesirable material are now commercially available. Some scientists propose to remediate ground water pollution by using nanoparticles of iron as a chemical reductant; in the process the iron oxidizes and becomes rust, a naturally occurring substance. Taking advantage of the high surface area of nanoparticles, magnetic iron nanocrystals are used to remove arsenic from drinking water. This method reportedly reduces, by more than 100-fold, the amount of waste produced by standard techniques. Another innovative approach involves coating the surface of iron oxide particles with molecules that selectively bind to pollutant molecules or ions. Introduced into water, the coated particles attract the pollutant and then a magnetic field is used to concentrate and recapture the bound pairs.

Saving energy and resources

Some new nanocatalysts can be used at room temperature. This is a huge advantage over traditional catalysts, which typically operate at high temperatures and require greater energy input. Capacity to function at room temperature paves the way for broad application of nanostructured materials in small-scale consumer and domestic products.

Nanotechnology may transform energy production, storage, and consumption by providing environmentally sound alternatives to current practices (Box 5). Severaltechnologies can enhance the efficiency of current energy sources and reduce carbon dioxide (CO_2)

emissions–including nanostructured catalysts for fuel cells, improved electrode materials in lithium ion batteries (Tarascon and Armand 2001), and nanoporous silicon and TiO_2 in advanced photovoltaic cells (Stalmans and others 1998, Pizzini and others 2005). Nanoscale optically selective coatings for windows can reduce energy consumption while also improving indoor air quality (Box 4).

Nanotechnology also shows significant potential in terms of saving resources. At the production stage, it offers opportunities to reduce the use of materials that have a large 'environmental footprint' by substituting others that have less impact, thereby promoting more efficient use of raw materials. Some effort is being made to produce nanostructured materials using renewable or abundant sources (such as substituting carbon-based nanoproducts for precious metals). This should be further supported by robust strategies for recovery or recycling of nanomaterials.

The use of high strength and lightweight nanomaterials may extend the lifespan of conventional materials such as plastics and save energy in transportation and other areas. For example, carbon nanotubes are molecular-scale cylinders of carbon that exhibit novel properties such as extraordinary strength, unique electrical properties, and highly efficient heat conductivity. This makes them potentailly useful in electronics, optics, and other applications of materials science. They will likely become widely used in common consumer products.

Public and private organizations have been quick to recognize the apparent benefits of nanotechnology, but there is a corresponding need to assess the full costs of this emerging field, including the life cycle costs of products. For example, many nanostructured materials save energy while being used but their manufacture may be very energy-intensive.

Cost-benefit analyses must take into account the true environmental impact of these materials—and the fate and transport of nanoparticles released in the environment must be more fully investigated.

THE ENVIRONMENTAL RISKS OF NANOTECHNOLOGY

Most new technologies are produced without full investigation of their long-term effects in the real-world environment—but nanotechnologies may present special potential risks which demand careful assessment. Although the quantity is less, the particle sizes are much smaller—small enough even to pass through skin or the blood-brain barrier. A large proportion of their atoms lie on the surface and could be highly reactive (Service 2005) (Box 6).

Scientists have been quite successful in characterizing and predicting the behaviour of nanoparticles in the laboratory. Foreseeing the environmental impact of their widespread use is much more difficult because of the complex physical, chemical, and biological interactions that come into play under real-life conditions.

To date, the potential environmental effects of engineered nanoparticles, in any quantity, are largely unknown. Three of the most pressing questions are:

i) how nanoparticles might change over time once present in the environment;
ii) what effect they might have on organisms; and
iii) what effect they might have on ecosystems.

Fate and transport of nanoparticles in the environment

Study of the fate and transport of nanoparticles is largely concerned with determining how their properties and behaviour change over time, particularly after release into the environment. At present, little is known about how nanomaterials might behave in different environments, including whether they remain relatively stable or change in ways that alter their anticipated impact.

The potential impacts of nanomaterials in all media should be fully investigated and compared to the impacts of conventional materials. This includes direct environmental impacts and also those that may ultimately affect human health. The answers will depend on the unique characteristics of each environmental medium. As with any compound, the potential impact (which might be positive, neutral, or negative) is linked to characteristics such as toxicity, bioavailability, mobility, stability, solubility, and reactivity.

Box 6: Small quantities, large effects

The quantity of nanomaterials currently generated, or predicted in the near future, is very much smaller than conventional commercial compounds. For example, the UK Royal Society and Royal Academy of Engineering (2004) estimate that total annual production of engineered nanomaterials will be approximately 58 000 tonnes/year for the period of 2011-2020. Such figures might be misleading. Nanoparticles may be produced in small volumes, but each cubic metre represents an enormous number of particles. Moreover, at the nanoscale the key characteristic is surface area rather than volume or mass. The net result is many tiny particles that are highly reactive. By contrast, according to the US Environment Protection Agency, millions of tonnes of carbon black are produced annually (EPA 2000). This nanoscale byproduct of the petroleum industry is commonly used for color or as reinforcement in rubber and plastic products.

Major types of nanoparticles anticipated to be commercially available in 2006-14

Product	2006-07	2008-10	2011-14
		Tonnes/year	
Nickel (carbon-coated) (Ni-C) powders	3 500	7 500	15 000
Poly (L-lactic acid) (PLLA) nanofibres	500	2 500	5 000
Yttrium Oxide (Y_2O_3) nanopowders	2 500	7 000	7 500
Ceria (CeO_2) nanoparticles, coatings	N/A	10 000	N/A
Fullerenes	N/A	300	N/A
Graphite Particles	1 000 000	N/A	N/A
Silica (SiO_2) nanoparticles, coatings	100 000	100 000	>100 000
Titania (TiO_2) nanopowders, thin layers	5 000	5 000	>10 000
Zinc Oxide (ZnO) nanopowders, thin films	20	N/A	N/A
		USD/year	
Carbon black	~ 8 billion	10 billion	12 billion
Carbon nanotubes	700 million	3.6 billion	13 billion

Source: NanoroadSME, a research project funded by the European Commission, 2006.

Air

Engineered nanoparticles can remain airborne over a long period because of their small size and light weight (Biswas and Wu, 2005). This may increase the likelihood that they will travel long distances, cross borders, and interact with gases and other airborne particles.

The properties of naturally occurring and incidental ultrafine particles (i.e., those having a diameter of ~100 nm) in the air are relatively well known and may serve as a basis for studying engineered nanoparticles that become airborne.

Water

There is a serious lack of data on bioavailability, biodegradation, and biotransformation of water-soluble nanoparticles. Natural small particles suspended and dispersed in water tend to aggregate, eventually becoming large and stable enough to precipitate out. The tendency and degree to which engineered nanoparticles aggregate in water is still under investigation, as are the mechanisms of precipitation. Even if they follow expected behaviour, it is not known what consequences this might have for bioavailability, toxicity, or exposure. Thus, little is known about how they might interact with organisms and affect the functioning of aquatic ecosystems.

Some studies are in progress. Scientists have begun investigating how current wastewater treatment processes affect and are affected by nanomaterials, as well as how the nanomaterial's solubility influences its toxicity, bioavailability, and mobility (Westerhoff and others 2006).

Many questions remain, such as how various aqueous conditions (salinity, phosphate levels, etc.) affect the stability of nanostructured materials that have been coated or functionalized to reduce or eliminate potential toxicity and exposure.

Soil

The fate of nanoparticles in soil is largely unknown. They may be 'partitioned' in ways that could influence where they reside and how they get there. Some may bind chemically to a soil particle; others may remain separate, residing either on the surface of soil particles or in the pore space between particles.

Scientists are attempting to map interactions between nanomaterial on soil particles and nanomaterial found in pores (Wan and others 2005). Biodegradability is a particularly important question: it is not yet known whether natural soil microbial populations will be able to efficiently and adequately degrade nanoparticles.

Addressing the knowledge gap

Life cycle analysis is one of the effective means of approaching the complex question of how nano-structured materials might affect the environment. It involves mapping fate and transport at every step, from production inputs to final disposal or dispersal. Currently available approaches to life cycle analysis should be modified in consideration of the lack of data for nanostructured materials.

The ability to measure and detect engineered nanoparticles, and to differentiate them from other nanomaterials, is vital to developing accurate fate and transport models for nanomaterials. Existing models, together with computer simulations, need to be explored further and systematically validated to determine their efficacy and accuracy for predicting where, when, and in what forms nanoparticles will ultimately be found in the environment, including whether or not they remain in the environmental medium into which they were initially released. Evaluating the potential environmental impacts of engineered nanomaterials prior to their mass production is essential to address environmental and human health concerns and to develop sustainable nanotechnologies. Even preliminary analyses can provide practical information that can be used to design or optimize processes that are more environmentally sound (Olsen and Jørgensen 2005).

Toxicology and health risks

So far, ecotoxicological studies on nanoparticles have been limited to a very small number of materials and target organisms. Data are lacking on the impact of nanoparticles on flora. Thus it is impossible to say with any certainty whether nanomaterials, which can be constructed from virtually any chemical structure, are similar to natural nanoparticles (which are mostly neutral or mildly toxic) or vastly different and therefore cause for concern.

The limited research done to date shows that certain nanoparticles may have ecotoxicological effects. For example, under laboratory conditions, fluorescent latex nanoparticles suspended in water were absorbed and accumulated into virtually all of the organs of the medaka fish (*Oryzias latipes*) and were taken up into medaka eggs. Toxicity to the eggs and uptake into

Box 7: Policy considerations for nanotechnology

The rapid emergence of nanotechnology creates a need for swift action by policy makers. Specific initiatives and programmes are needed together with appropriate financial and human resources, to achieve the following:

- Standardize nomenclature and test protocols to ensure maximum comparability of test results and to facilitate generalization of findings
- Foster cooperation between public and private sectors, between developed and developing countries, and among developing countries
- Sensitize national regulatory and environmental agencies to the potential opportunities and risks of nanotechnology (environmental, human health, and socio-economic)
- Support research and development of nanotechnology applications that contribute to sustainable development
- Evaluate the potential environmental and human health impacts of engineered nanomaterials, giving priority in this to materials that are already being mass produced and potentially released into the environment
- Identify, evaluate, and share private sector risk management methods and best practices for nano-scale materials (including worker safety and material handling procedures)
- Mobilize the existing knowledge of and lessons learned from chemical policies related to environmental and health issues, to help address nanotechnology challenges
- Educate the public about the benefits and risks of nanotechnology, raise awareness, and provide access to information about health and environmental impacts
- Encourage co-operation between governments and intergovernmental organizations to address and share information on the impact of nanotechnologies on the environment and human health.

the body of the adult fish depended upon the size of the nanoparticles and on external factors such as the salinity of the water (Kashiwada 2006).

The toxicological behaviour of nanomaterials that come into contact with cells depends on properties such as chemical composition, quantity, solubility, shape, and characteristics such as area and charge. The effects may also be influenced by factors such as persistence (how long a nanoparticle remains intact) and bioaccumulation (how many nanoparticles accumulate within a biological system) (SCENIHR 2005). Impurities that result from production processes also affect the toxicity of a given nanoparticle. The means of exposure also plays a significant role. Additional features, such as translocation and accumulation of particles within particular organs, must be considered (Oberdörster and others 2004).

Some air pollution studies have examined incidental (non-engineered) nanoparticles, mainly from combustion exhausts. However, research to date suggests that it is not possible to generalize about the toxicological behaviour of nanoparticles. They do not always mirror the characteristics of the bulk material from which they derive nor can existing data on one product be extrapolated to all nanoparticles.

Moreover, different species of plants and animals exhibit different sensitivities. For example, titanium dioxide (TiO_2) is frequently used in surface coatings and cosmetics, including sunscreen products. Studies indicate that cellular absorption of TiO_2 particles through healthy skin is very limited (Schulz and others 2002). However, in laboratory tests, when TiO_2 particles were released in aquatic environments (as might occur through swimming or washing), they were potentially harmful for algae and water fleas (*Daphnia spp.*) (Hund-Rinke and Simon 2006).

Other studies show that carbon nanotubes have toxic properties when absorbed through the skin (Monteiro-Riviere and others 2005). More controversial is whether inhalation or ingestion of carbon nanotubes, or of impurities associated with their production, cause lung damage in experimental animals (Lam and others 2004, Donaldson and others 2006, Shvedova and others 2005, Wörle-Knirsch 2006). Further research and testing is needed in this area to provide a scientific basis for policy frameworks to deal with the uncertainties and risks.

Fullerenes are a particular type of nanoparticle, composed entirely of carbon atoms in the form of a hollow sphere, ellipsoid, or tube. Fullerenes show strong toxicity to bacteria (Lyon and others 2005). Among fish species, studies on fullerene exposure show contradictory results—ranging from no negative impacts to 100 per cent mortality (Oberdorster 2004, Zhu 2006). Again, further investigation is needed, using appropriate methodologies.

Titanium dioxide is a nanomaterial used in sunscreensbecause it blocks ultraviolet radiation with only limited absorption by healthy skin.

Source: AP Photo/Mary Godleski

Further reseacrh

Additional studies are needed to clarify whether existing methodologies for assessing ecotoxicological effects are adequate for nanomaterials or if alternatives need to be developed.

It is widely accepted that the traditional methods of measuring dose exposure are of little use for predicting the toxicological effects of nanoparticles. Standard monitoring instruments cannot always detect nanoparticles in environmental samples. Thus, characterizing their behaviour and novel properties, and tracing their impacts, presents a real scientific and technical challenge.

To assess the health risks for human beings and other terrestrial mammals, toxicity test data on rats, mice, and other species can be useful. Existing literature contains contradictory data, but a growing body of evidence suggests that some nanoparticles may represent an additional challenge, since they have an enhanced capability to reach internal organs that are not normally exposed to larger particles.

In addition, there is a need for studies that examine the long term effects of nanoparticles on different environments and their resident organisms.

Experience so far shows that exhaustive assessment of existing data and new, carefully designed research are required to establish the ecotoxicity of nanoparticles, including how each differs from conventional forms of the same substance. Assessing the ecotoxicity of novel nanoparticles that have no naturally occurring counterpart may require a different approach.

LOOKING AHEAD

Nanotechnology is no longer ‘on the horizon’; it is fast becoming a facet of daily life. The nanoproducts now available came onto the market with limited public debate and with limited additional regulatory oversight that is specifically aimed at their novel features. Current research and development seek to rapidly exploit the novel applications of nanomaterials.

Considering the large-scale investments in product development, public authorities have an important role in assessing and addressing the complex implications, both short and long term, of broad dissemination of nanotechnology. This is particularly true in relation to nanoparticles that might be released, intentionally or unintentionally, into the environment.

It may be possible to regulate nanotechnology products under some of the existing laws against pollution. For example, late in 2006 the US Environmental Protection Agency (EPA) announced that it would require manufacturers using nanosilver to provide scientific evidence that such usage will not harm waterways or public health. Nanosilver is used to kill germs in shoe liners, food-storage containers, air fresheners, and washing machines (Heilprin 2006).

It is not clear whether current regulatory frameworks are adequate to deal with the special characteristics of nanotechnology. To date, no government has developed a regulatory framework specific to nanotechnology. Some governments are making considerable efforts to determine whether existing regulatory frameworks are sufficient for addressing issues associated with nanotechnology and its potential societal impacts, or whether modified or completely new risk management approaches are needed. As an example, the US EPA is developing a white paper on nanotechnology policy (US EPA 2006).

A number of complementary measures will be needed, ranging from carefully conducted laboratory experiments and computer simulations to small-scale field trials. It will also be necessary to develop standards and instrumentation that can accurately characterize and monitor the effects of these novel materials. As many unforeseen and unintended consequences on the environment are long term, it may be necessary to adapt existing protocols for traceability and life cycle analysis of products—or to devise new ones.

Governments and international organizations should work together with scientists and the private sector to establish scientifically and ethically sound, risk-based standards for new nanotechnology-based products, and to promote 'best practices' to avoid potential health and environmental threats. Standard nomenclature is also needed to eliminate ambiguity when communicating differences between nanomaterials and bulk materials, as well as in reporting for regulatory purposes.

Today's globalized world offers an unprecedented opportunity to develop, disseminate and share the benefits of technical innovation to more users, more rapidly. It will be important to avoid the development of a 'nano-divide' between nations with advanced nanotechnology programmes and those without (Balbus and others 2005).

Scientific understanding of environmental processes is increasing, as is general awareness of environmental issues. However, policy makers, industry, non-governmental organizations, and scientists need to work together to raise public awareness of the specific opportunities and risks associated with nanotechnology. They also need to inform the public on steps being undertaken to assess the potential consequences of nanomaterials before they reach the marketplace.

Nanotechnology creates many new possibilities for social and economic development, both in the short and long terms. The enhanced capacities to monitor the environment, to increase energy efficiency, and to reduce the impact of human activities on the environment are clear potential benefits in the adoption of nanomaterials. A balanced approach is required to maximize benefits while minimizing risks.

Research and development of nanotechnologies are science policy priorities in some developing countries, resisting traditional technological divides between developed and developing countries.

Source: Joerg Boethling / Still Pictures

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