



Nano and the Environment: Potential Risks, Real Uncertainties & Urgent Issues

Biosafety Brief 2011/01

Biosafety Brief 2011/01
GenØk - Centre for Biosafety
Tromsø, Norway

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Summary

Nanoscale sciences and technologies (nanoST) are extremely diverse and therefore difficult to define. Claims are being made about both their potential benefits and risks, yet there is currently very little knowledge on their environmental ramifications. The high levels of scientific uncertainty involved mean that more risk-oriented research is crucial. However, it must also be recognized that a comprehensive and robust risk appraisal of nanomaterials is not currently possible. In this situation of high uncertainty, decisions still have to be made. Since these will inevitably be based not only on what we know, but also on what we value and prioritise, reflection on social and ethical dimensions is particularly important. Decision-making processes capable of transparently integrating risk oriented research with social and ethical aspects are therefore essential.

This Biosafety Brief outlines central issues facing the environmental governance of nanoST. It begins by discussing nanoST and its definitional difficulties. It then moves on to examine potential risks and real uncertainties as well as social and ethical dimensions. Consideration is also given to regulatory developments on both the national and international level, including challenges raised by the convergence between nano and biotechnologies. These issues are then profiled in the context of three case studies: the use of nanosilver, carbon nanotubes and nanoparticles for environmental remediation.

The Brief concludes with seven recommendations for the environmental governance of nanoST:

- Move away from generalised discussions towards a recognition of case specific differences
- Encourage better characterisation of nanomaterials and require reporting on their use
- Increase funding for research on (eco)toxicology and environmental fate and behaviour
- Use lifecycle perspectives when considering environmental impacts
- Develop international standards flexible enough to adapt to new methods and findings
- Include social and ethical considerations in policy making, especially in the framing of priorities for risk research
- Commit to environmentally sustainable and socially robust innovation

The authors would like to acknowledge and thank Katrine Jaklin for designing the layout for this report and Anne Ingeborg Myhr for helpful comments on an earlier draft.

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Nano & the Environment

Nanotechnologies are both praised for offering potential environmental benefits and scorned for creating new environmental risks. In this document, we give an overview of the existing and emerging environmental issues relating to nanotechnologies by highlighting general problems and spotlighting three specific cases (nanosilver, carbon nanotubes, and nanoparticles used in environmental remediation). We conclude by describing overarching themes of importance for nano in the environment, and offer recommendations for research and regulatory attention in this area.

What is ‘nano’?

While ‘nano’ as a scientific prefix refers to one billionth (e.g. a nanometer = 10^{-9} m and a nano second = 10^{-9} s), the term is increasingly used to refer to sciences and technologies that operate at the level of atoms and molecules. This has led to the term referring to an incredibly diverse range of activities and objects, with ‘nanoscience’ occurring across various disciplines (e.g. physics, chemistry, biology, materials science, information technology, engineering) and ‘nanotechnology’ being applied across a broad range of sectors (e.g. energy, transport, medicine, textiles, communications, agriculture). While it is common to refer to ‘nanotechnology’ in the singular, the diversity involved arguably makes it more appropriate to use plural terminology, such as ‘nanoscale sciences and technologies’ (nanoST).

The motivation for delineating nanoST as something new and unique is that objects at the nanoscale (see Box 1) can express novel properties, that is, properties that are not expressed by the same material at larger scales. For example, properties of materials such as colour, conductivity, reactivity and melting point can change as you move down to the nanoscale. Such novel properties may result from an enhanced significance of quantum effects, a higher surface area/volume ratio and/or an alternative arrangement of atoms. Most definitions note that objects can be nanoscale in one, two or three dimensions and emphasise that nanoST involve actively investigating and utilising the novel properties of this scale. Since various scientific disciplines operate on the nanoscale, there is also a potential for convergence between fields (for more on ‘converging technologies’ see Box 4).

Potential Risks and Real Uncertainties

Given the incredible diversity involved, it is not possible to ascribe a single risk/benefit profile to nanoST as a whole. There is, however, broad scientific consensus that the novel properties of nanomaterials mean that their potential environmental impact cannot be simply derived from knowledge of their bulk counterparts [1]; i.e. that they need to be assessed individually as new

Box 1 - The Nanoscale

The nanoscale is often defined as 1-100nm because this is the range within which novel properties are most likely to occur. However, both the upper and lower limits of this range remain subject to debate. There is therefore an emerging trend towards maintaining flexibility in formal definitions so that the function of unique properties rather than a fixed nm range is used to define the nanoscale. This is important, because unlike legal definitions, novel toxicological profiles may not be confined to a 100nm limit. That is, novel properties may also be apparent at 200, 300 or 500nm. Defining the boundaries of ‘the nanoscale’ is politically significant, with the potential to affect both research funding and regulatory action.

materials. Emphasis has therefore been placed on the need for regulatory attention on nanoST (for the Norwegian context see Box 2), including standardised guidelines for regulatory science (see Box 3) and enhanced research on potential health and environmental impacts. However, despite consistent calls for more research in nano(eco)toxicology, the current level of knowledge has been described as ‘rudimentary’ [2] and the level of uncertainty ‘extreme’ [3]. Uncertainty arises because the toxicological potential of particular nanomaterials relates to a suite of different factors all of which are currently poorly understood. For example, in addition to the traditional dose metrics of mass or number, the toxicological potential of nanomaterials relates to characteristics such as surface area, shape, solubility and agglomeration state, which may be altered by environmental factors such as pH, salinity and the presence of organic matter, etc. [4]. Other factors of importance for understanding environmental impact, such as levels of exposure and the fate and behavior of nanomaterials in the environment, are also subject to high levels of uncertainty [5]. These uncertainties are exacerbated by a current lack of appropriate and agreed methods for testing, including basic issues such as how to detect, measure, and characterise nanomaterials [6], impacting both the reliability and the generalisability of research outcomes. In summary, there is currently very little knowledge on the characteristics, ecotoxicity and environmental fate of the various nanomaterials in use and effective methods to perform this type of research remain substantially underdeveloped.

While research in nano(eco)toxicology remains shrouded in uncertainty, emerging evidence indicates a potential for harm. Most concerns relate to engineered nanoparticles not embedded in a solid matrix. Free nanoparticles demonstrate extreme mobility, including an ability to penetrate cell membranes. If they enter the blood stream/lymphatic system they can move throughout organisms. It has been demonstrated that they can enter organs such as heart, liver, lungs, kidneys, spleen, and brain, as well as reproductive and nervous systems, and even be transferred to a foetus [7-10]. It has also been found that nanoparticles can bind to other chemicals and pollutants and thereby enhance their biological availability and toxicity [11] in what has been termed the ‘Trojan horse effect’. Reviews of the research available on particular classes of nanomaterials are starting to emerge [5, 7, 12] as are online databases of available health and environmental safety research, e.g. from the OECD [13], ICON [14], and PEN [15]. While the toxicity of free nanoparticles cannot be generalised, emerging evidence for characteristics such as mobility, persistence and bioaccumulation is central to environmental concern.

To understand the potential impact that any nanomaterial will have on the environment, the adoption of a lifecycle perspective is necessary. This involves assessing impacts that may occur throughout a product’s “life”, including the phases of manufacture, distribution, use and disposal (see Figure 1). The timeframe over which such an assessment should take place will necessarily vary with the product in question and its receiving environments. Both the process of performing a lifecycle assessment [16] and the determination of its relevant timeframe will need to be informed by case specific scientific research.

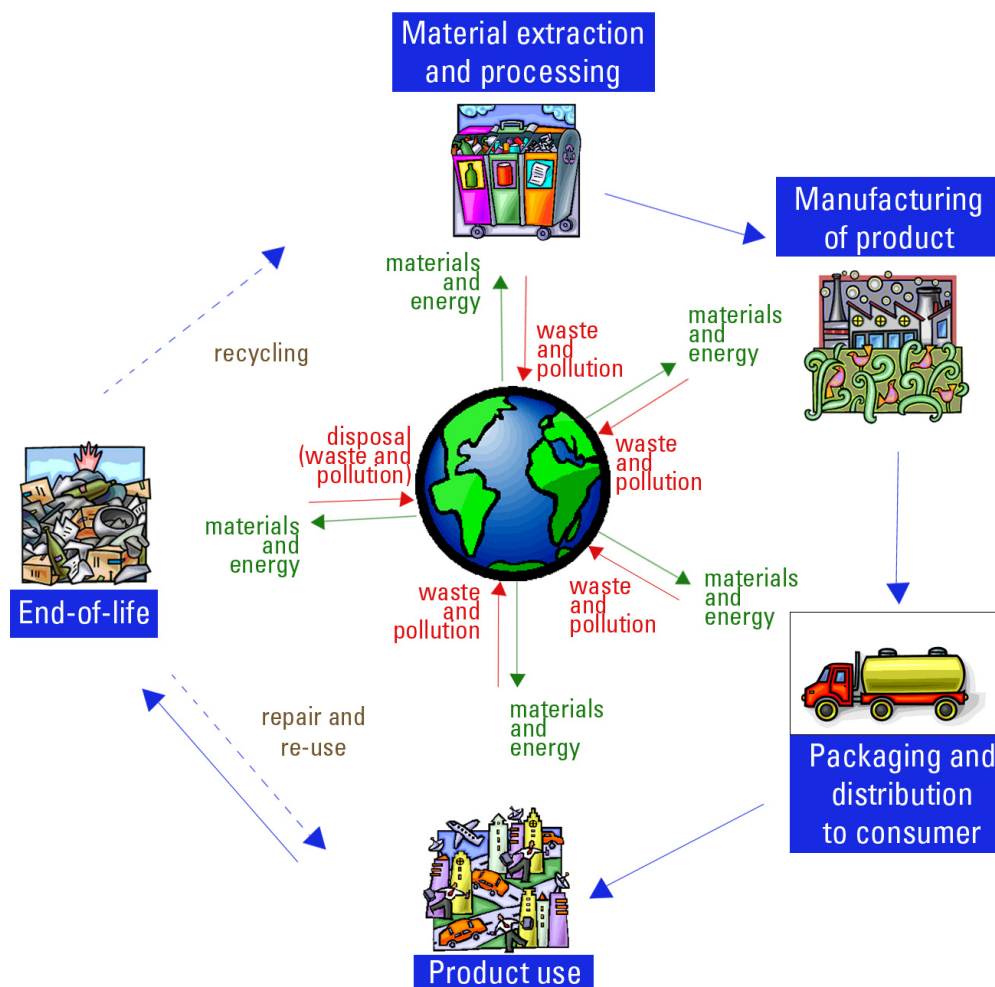


Box 2:**Developing International Standards & Codes of Conduct for NanoST**

The development of standardised terminology, characterisation methods, test protocols, and risk assessment processes for nanomaterials is a priority internationally, with major initiatives on the topic currently underway within both the OECD and the ISO. The work of the OECD Working Party on Manufactured Nanomaterials [17] includes maintaining a database on human health and environmental safety research, investigating the role of alternative methods in nanotoxicology, developing harmonised test guidelines and safety testing a representative set of manufactured nanomaterials. The Nordic Council of Ministers is a co-sponsor of the work on safety testing silver nanoparticles and a contributor to the safety testing of iron nanoparticles. The ISO technical committee on nanotechnologies (TC 229) is working to develop international standards for terminology and nomenclature, measurement and characterisation, health, safety and environmental aspects (including standards for environmental risk assessment) and material specifications [18]. The ISO also has technical groups on consumer and societal dimensions as well as sustainability. Although Standards Norway has established a committee of experts for participation in TC229, their continued involvement is currently uncertain and dependent on the availability of financial resources.

The process of creating international standards for nanoST is taking place at the same time as the development of basic methods and exploratory research. While standards are urgently needed, the current search for 'anticipatory standards' represents an attempt to standardise something that is yet to come. Facing this dilemma, the development of codes of conduct [19] may be regarded as a complementary approach. The European Commission's code of conduct for responsible nanoST research [20] is one example of this, which includes principles of sustainability, precaution and accountability at its core.

Figure 1. A Lifecycle Perspective



Box 3: Nano in Norway

It is very difficult to obtain a robust overview of the state of nanoST in terms of research, development, and products due to the lack of common definitions (see Box 1), and the fact that it is not currently mandatory to register nanoST research or label nano products in Norway. What follows is an attempt to provide information despite these limitations.

Products

In June 2010, 19 ‘nano’ products were *voluntarily* registered by companies in the Norwegian “registry of products” (Produktregistret) [24]. However, research conducted in Denmark in 2007 identified 343 consumer products containing nanostructured materials [25], while a global database indicates over 1000 nano consumer products available in 2010 [21]. These products are predominantly related to surface treatments, cosmetics and sports equipment and there seems little reason to believe that many of the globally identified nano products would not also be available in Norway.

Research and development

In Norway there is currently a greater orientation towards research and development in nanoST than the production of commercial products. In 2010, for example, 21 companies reported being active within “production, import, research and development” of nanomaterials in Norway, while only 3 of these were production companies [24]. The research landscape for nanoST in Norway is dominated by a number of research institutions that have developed extensive and dedicated research strategies for nanoST. These include NTNU [26], UiO [27], SINTEF [28], IFE [29] and UiB [30]. At NTNU, UiO and SINTEF, large investments have also been made in new nanoST laboratory infrastructure (most notably including clean room facilities). The “Nanomaterials and new materials” (NANOMAT) programme of the Research Council of Norway is the most important source of funding for Norwegian nanotechnology research and the primary objective of this program is to develop technical excellence in functional materials in Norway, while prioritising environmental friendly technologies. Other sources of funding for research on nanoST in Norway include the general programs of ELSA for research into social and ethical dimensions as well as Miljø 2015 for research focused on environmental impacts.

Regulation

In Norway, there are currently no specific regulatory frameworks for nanoST. Applications in different fields will be subject to existing regulatory frameworks (e.g. in medicine, cosmetics and food), however these frameworks may not recognise nanomaterials as ‘new’ materials and therefore potentially in need of special attention. The majority of nanomaterials will be subject to the recently introduced framework for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). Building on precautionary thinking, REACH employs a “no data, no market” principle. The REACH framework requires extensive safety documentation for materials produced or imported in high quantities. However, it is problematic that many nanomaterials may not meet the tonnage threshold required to trigger extensive safety documentation. Additionally, and as indicated previously, mass may also not be the most relevant characteristic for understanding nanotoxicity. Within REACH efforts are being made to address such limitations.

Social and Ethical Dimensions

The continued commercialisation of nanotechnologies in the face of the extreme uncertainty concerning health and environmental impacts raises a range of social and ethical issues. Central for this report is the way values, beliefs and assumptions influence decision-making in both risk-based science and policy. The evaluation of environmental impacts of new technologies has traditionally been approached through a framework of risk, i.e. through science-based risk assessment. However, this framework has been criticised for masking the social values involved and for marginalising ethical issues [22]. For nanomaterials, a sound scientific risk assessment is not possible either now or in the near future due to the lack of knowledge and agreed methods and standards for testing. It has, for example, been suggested that toxicity testing on just the nanomaterials already commercially available would require decades to complete and the investment of over one billion US dollars [12, 23]. Given the challenges to empirically understand the potential environmental impact of nanomaterials, there is a clear need to set priorities for research. This includes deciding what nanomaterials pose the most significant potential risks, what organisms are most useful to study, what methods are most relevant to use and whether traditional toxicological or emerging ecological models for assessing environmental risk are the most appropriate. This prioritisation process inevitably involves values. It also draws in ethical issues such as the appropriate relationship between humanity and nature and what constitutes reliable and sufficient knowledge for decision-

making. Finding ways to integrate the development of high quality science with broad-based deliberation over social and ethical questions is therefore a central challenge for decision-making under the conditions of uncertainty. Developing a better understanding of how science, ethics and public values are intertwined in the setting of research trajectories and the choice of regulatory actions is also arguably necessary if responsible and reflexive environmental governance of nanoST is to be possible.

Case Studies

So far we have suggested that 1) NanoST is incredibly diverse, 2) Claims are being made about its potential for both environmental benefit and risk, 3) There are high levels of uncertainty concerning actual environmental impacts, and 4) There is a need to consider social and ethical dimensions when discussing biosafety issues connected to nanoST. In what follows we spotlight 3 different cases of nanoST to demonstrate these points in more concrete terms. These cases are the use of nanosilver, carbon nanotubes and iron nanoparticles for environmental remediation. In each case we highlight dual benefit/risk claims and discuss available research relating to ecotoxicity. We conclude by arguing that while lifecycle perspectives are crucial for understanding the environmental impact of nanoST, current limitations for performing these make integrating social and ethical considerations especially important.

Case Study 1: Nanosilver - silver bullet or environmental pollutant?

Nano-sized particles of elemental silver (nanosilver) represent one of the most widespread applications of nanotechnology today [31]. While silver's antibacterial effects have been utilised since ancient times, nanosilver is particularly effective at combating pathogens (mainly bacteria, but also viruses and fungi). In this function, nanosilver is for example being used for disinfecting water supplies (e.g. in hospitals), in dressings for wounds, burns and ulcers, in medical devices, food packaging, clothing and in a range of household goods such as refrigerators and washing machines [32, 33].

In spite of its wide range of applications, surprisingly little research exists on the toxicity and fate of nanosilver within organisms and ecosystems [31, 34]. Conducted in vitro research indicates that nanosilver particles are able to penetrate cell membranes, can accelerate the generation of cellular reactive oxygen species and lead to cytotoxic and genotoxic effects (i.e. toxicity at a molecular level, including DNA damage [35-37]. One of the key areas of uncertainty, however, is whether any observed toxicity relates to silver nanoparticles themselves and/or to the release of silver ions [31]. Ionic silver is known to be a toxic metal for aquatic organisms and in vivo studies investigating the impacts of nanosilver on zebra fish have shown an ability for the nanoparticles to cross the protective membrane of embryos, become embedded in developing organs and lead to dose dependent deformities and deaths [38, 39].

Concerns related to the extensive use of nanosilver relate include the development of resistance among pathogens [32] and the persistence of the material creating a threat for biological (particularly microbial) diversity [33]. Certain types of nanosilver containing textiles (e.g. 'odour free' nanosocks), have been found to leach considerable amounts of colloidal or ionic silver [40]. This has led to concerns that nanosilver may have negative effects for aquatic environments and for the use of treated waste sludge as agricultural fertilizer [33, 41, 42]. These concerns emphasise the importance of considering long timeframes and the full life cycle of a nano product in assessing its environmental impact [16], including how the product may affect populations over generations and how it may circulate through waste systems. In Norway, the interest organisation "Norwegian Water" raised these types of concerns in relation to the sale of laundry machines utilising nanosilver, i.e. "Silver Wash" as marketed by Samsung Electronics Nordic. In a public letter, Norwegian Water asked the national Climate and Pollution Authority (and the Norwegian Food Safety Authority) to examine the health and environmental consequences of this laundry system. The Climate and Pollution Authority asked for a risk assessment to be conducted by Samsung, but found the information they received to be insufficient. The authority requested more information, however, that delivered was also deemed inadequate for assuring the product's safety. The Climate and Pollution Authority accordingly requested that the use of "Silver Wash"

be restricted to temperatures < 60 °C (as higher temperatures would make the bactericidal effect of silver redundant). Further, they requested Samsung to inform consumers thoroughly about the function of nanosilver and what should be done to protect the environment from the subsequent discharge into waste water systems. With reference to the precautionary principle, these requests were aligned with requirements imposed by Swedish authorities. Samsung no longer offers “Silver Wash” laundry machines for sale in Norway.

Case Study 2: Carbon Nanotubes – Energy saved or squandered?

Carbon nanotubes (CNTs) represent one of the ‘boom areas’ of nanoST, with a predicted global market of over US\$800 million by 2011 [43]. CNTs are carbon atoms arranged into cylinders (unlike into the sheets of graphite or the tetrahedrons of diamond), which enables attractive attributes such as an incredible high strength/weight ratio and unique electrical properties. These characteristics are motivating the investigation and use of carbon nanotubes in areas as diverse as electronics, transport, energy, optics, architecture and medicine. Claims to environmental benefits from CNTs typically relate to the creation of new strong/lightweight materials for the transport industry resulting in reduced fuel use and their potential role in improving the efficiency of renewable energy technologies.

Since carbon nanotubes share a structural similarity to asbestos (i.e. both are small, needle-like, stiff fibres) a pressing question has been whether nanotubes could pose similar risks. Available research has shown that CNTs may cause inflammation and granulomas (scar-like lesions) [44-50] which are indeed the same bodily responses that result from exposure to asbestos and precede the development of cancers such as mesothelioma. Furthermore, it has been demonstrated that CNTs may cause skin-cell toxicity through dermal exposure [51] and genotoxicity [52]. CNTs can be single-walled or multi-walled and come in a range of different sizes; they tend to agglomerate (a common feature of free nanoparticles), and can contain different amounts of residues from metal catalysts used during their production. Since such factors may impact their toxicity, different types of CNTs will pose different levels of risks.

There is currently extremely limited information available on levels of exposure to CNTs. Available studies focus on worker exposure in nanotechnology industries and R&D facilities [53, 54], which says little about environmental exposures and does not account for the expected increase in exposure as the use of CNTs becomes more widespread. It is also important to take into account the incredible persistence of CNTs, which have been referred to as probably one of the most biologically non-degradable man-made materials currently available [49].

Challenges to understanding the risks posed by CNTs relate not only to the limited information available but also to a deep-level debate about the paradigms, methods and approaches that are most appropriate for testing. For example, in studies designed and conducted according to a fibre-toxicology paradigm, long nanotubes appear most toxic. However, if tested according to the methods and approaches most relevant for particles, short nanotubes may also demonstrate significant toxicity [44]. There is therefore a need for more exploratory research and experimentation with test methods before any standardised testing procedures are put in place.

Just as for nanosilver, it is crucial to perform a full lifecycle assessment [16] to understand the net environmental impact of CNTs. This is because not only are there serious concerns relating to the toxicity and biopersistence of CNTs, their production is also highly energy intensive [55] and may outweigh the savings achieved in their application. Comprehensive energy accounting is therefore a necessary component in any lifecycle assessment of CNTs.

Case Study 3: Nanoparticles for environmental remediation – pollutants in or out?

The use of nanoparticles for improved *in situ* environmental remediation of polluted soils and groundwater is held up as one of the most promising areas for nanotechnology to offer environmental benefits. In 2010, nanoparticles were being used for *in situ* environmental remediation on approximately 60 sites across North America, Europe and Asia [56]. Currently, the use of zero-valent iron and bimetallic nanoparticles (e.g. incorporating manganese, nickel, palladium and zinc) predominates [58], although the potential of nanoscale zeolites, enzymes, metal oxides and carbon

nanotubes are also all being explored [58]. The benefits of using nanoscale particles for remediation include the possibility to degrade a larger range of contaminants, reduce degradation times, and create less toxic intermediate products [59].

While the benefits seem clear, the potential risks associated with these technologies have not been substantively researched and remain poorly understood [58, 60]. This is important because nascent research on the toxicology of nanoparticles used for remediation does indicate a potential for undesirable impacts. Notable observations include cytotoxic effects from oxidative stress, a physical disruption of cell membranes, and ecological impacts such as altered microbial population dynamics [61, 62]. Further research is certainly required on the fate, transport and persistence of these nanoparticles in the environment, as well as on their toxicological potential for biological (including microbiological) systems. Furthermore, since these factors will vary across the particles used, any surface coatings applied, and the hydrogeological contexts of application [61], research on their environmental impact should ideally be conducted on a context specific basis.

The main challenges facing efforts to use nanoparticles for environmental remediation include rapid oxidation decreasing the reactivity of the particles, a tendency for nanoparticles to aggregate and agglomerate, and limited distribution of injected particles due to agglomeration. Interestingly, strategies being pursued to overcome these challenges (such as surface coatings and multiple treatment injections), result in exactly the types of characteristics that might be undesirable from the perspective of ecotoxicology, i.e. increased mobility, exposure, persistence and reactivity.

When thinking about the environmental issues involved in this case, it is also important to adopt a lifecycle perspective, not only in terms of questioning what happens to these particles after they have served their purpose of degrading the contaminant, but also in terms of production, including for example questions about the sustainability and desirability of using rare and heavy metals in bimetallic nanoparticles. In an even broader perspective, this case calls for social and ethical deliberation on the use and mentality of ‘technological fixes’ to environmental problems. This would include considering the potential for generating an over-optimism concerning our abilities to repair environmental damage, as well as the potential that a focus on the availability of such fixes may inadvertently create an acceptance or apathy towards generating the initial harm.

Box 4. Converging Technologies: Nano meets Bio

As various scientific disciplines operate on the nanoscale, interaction between these fields can facilitate the creation of ‘converging technologies’. For example, a grand vision has been put forward that convergence between nanotechnology, biotechnology, information technology and cognitive science will lead to a new renaissance in science and technology [63]. Of particular relevance for environmental legislation today is the interface between nanotechnology and biotechnology.

Nanobiotechnologies

Advances in nanobiotechnologies are numerous and occurring across various sectors. One prominent area of development is the targeted delivery of DNA, proteins and drugs to specific cell or tissues. Here, the convergence of nanotechnology with biotechnology is allowing for the introduction of genetic modifications, gene expression regulation and therapeutic agents with greater precision, scope and complexity than previously possible. Other key areas include the use of nanoparticles and nanostructures in medical diagnostics (for both basic research and disease identification) and the use of biological entities such as DNA and viruses in the development of molecular electronics.

Regulatory issues

The adequacy and relevance of existing environmental legislation to nanobiotechnologies is unclear. In the case of targeted delivery, current applications focus on contained use or the early stages in the process of creating a genetically modified organism (GMO). Therefore, some biotechnology legislation (e.g. Norwegian Gene Technology Act) may not apply as these uses often fall outside their defined scope. However, developments in this converging field are unpredictable and regulators should remain attentive to new advances. For areas such as medical diagnostics and molecular electronics, the adoption of a lifecycle perspective raises questions about which legislation applies and which regulatory agencies have responsibility for environmental protection. For example, when nanoparticles are used in a medical diagnostic, is it clear how the environmental impact of

the manufacture and disposal of this device will be regulated, and whether it will be sufficiently sensitive to the novel toxicological properties of nanomaterials? When a genetically modified virus is used to assemble electronic components, how will any potential environmental impacts be assessed and by whom? A lack of clarity on such issues may lead to inadequate safety assessment of converging technologies. Therefore the development of converging technologies and its relationship to regulatory policies should be subject to a more detailed investigation than has been possible in this Brief.

Conclusions and Recommendations

The environmental governance of emerging technologies faces the challenge of striking a balance between maximising benefits while avoiding unacceptable harms. For nanoST this must be pursued in a situation where high scientific uncertainty predominates. Here, perceived benefits must be weighed against largely unknown risks, and short term impacts against long term uncertainties. The adoption of a lifecycle perspective emphasises that short term environmental benefits be considered alongside the possible long term impacts of a products manufacture, distribution, use and disposal. This would require more detailed research on ecotoxicity and the fate and behaviour of nanomaterials in complex ecosystems. However, it would be naïve to believe that the governance challenges involved can be simply addressed through funding more risk-oriented science.

The environmental governance of nanoST represents a ‘post-normal’ situation where “facts are uncertain, values in dispute and decisions urgent” [64]. While more risk-oriented research is crucial, comprehensive risk assessment for nanomaterials is neither presently attainable nor would it alone ensure good governance. Given the complexities involved, decisions must be made using incomplete information. These decisions will not only be informed by what we know, but also by what we value and prioritise. It is therefore important that these values are made explicit and open to deliberative negotiation with a broad range of citizens and stakeholders. Deliberation over decision-making in the face of uncertainty need not address ‘nanotechnology’ as an undifferentiated whole. Revolving around articulations of matters of concern, ethical positions and visions of the good life, discussions could be very case specific. For example: Is it desirable to incorporate nanosilver into clothing and household goods if its overuse could lead to problems regarding resistance and wastewater treatment? Given the potential toxicity, biopersistence, and significant energy use of CNTs, what applications might be deemed trivial or undesirable vs. essential and compelling? What is our role in the biological community and do we have a duty to repair environmental damage? Good governance of nanoST requires both increased risk oriented research and its integration with these types of social and ethical questions.

We therefore conclude by offering the following recommendations for the environmental governance of nanoST:

- **Move away from generalised discussions towards a recognition of case specific differences**
- **Encourage better characterisation of nanomaterials and require reporting on their use**
- **Increase funding for research on (eco)toxicology and environmental fate and behaviour**
- **Use lifecycle perspectives when considering environmental impacts**
- **Develop international standards flexible enough to adapt to new methods and findings**
- **Include social and ethical considerations in policy making, especially in the framing of priorities for risk research**
- **Commit to environmentally sustainable and socially robust innovation**

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