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Nano and the environment – Part I: Potential environmental benefits and sustainability effects

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Summary

Nanotechnology products, processes and applications have the potential to make important contributions to environmental and climate protection by helping save raw materials, energy and water as well as by reducing greenhouse gases and problematic wastes. Nanomaterials, for example, can increase the durability of materials; dirt- and water-repellant coatings are designed to help reduce cleaning efforts; novel insulating materials can improve the energy efficiency of buildings; adding nanoparticles to reduce the weight of materials can help save energy during transport. Great hopes are being placed on nano-technologically optimized products and processes that are currently under development in the energy production and storage sectors.

Emphasis is often placed on the sustainable potential of nanotechnology, but this in fact represents a poorly documented expectation. Determining a product's actual effect on the environment – both positive and negative – requires considering the entire life cycle from the production of the base materials to disposal at the end of its useful life. Only few life cycle analyses have been conducted, but some show clearly reduced environmental impacts or energy and resource savings for certain products that use nanomaterials or nanotechnology processes. Nonetheless, not every "nano-product" is a priori environmentally friendly or sustainable, and the production of nanomaterials often requires large amounts of energy, water and environmentally problematic chemicals.

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Introduction

Nanotechnology is often referred to as being a "key technology" of the 21st century, and the expectations for innovative products and new market potentials are high. The prediction is that novel products with new or improved functionality, or revolutionary developments in the field of medicine, will improve our lives in the future. Importantly, these technical innovations have also raised great hopes in the environmental sector[1]. Nano-technological products, processes and applications are expected to contribute significantly to environmental and climate protection by saving raw materials, energy and water as well as by reducing greenhouse gases and hazardous wastes. Using nanomaterials therefore promises certain environmental benefits and sustainability effects, which are outlined in this dossier. Note, however, that nanotechnology currently plays a rather subordinate role in environmental protection, whether it be in research or in practical applications. Environmental engineering companies themselves attach only limited importance to nanotechnology in their respective fields[2].

Beyond the potential environmental benefits, the potential threats and risks also require close scrutiny and are increasingly becoming the focus of research efforts. The dossier 027en "Nano and the Environment – Part II" provides an insight into that aspect.

Potential environmental benefits

Rising prices for raw materials and energy, coupled with the increasing environmental awareness of consumers, are responsible for a flood of products on the market that promise certain advantages for environmental and climate protection. Nanomaterials exhibit special physical and chemical properties that make them interesting for novel, environmentally friendly products. Examples include the increased durability of materials against mechanical stress or weathering, helping to increase the useful life of a product; nanotechnology-based dirt- and water-resistant coatings to reduce cleaning efforts; novel insulation materials to improve the energy efficiency of buildings; adding nanoparticles to a material to reduce weight and save energy during transport. In the chemical industry sector, nanomaterials are applied based on their special catalytic properties in order to boost energy and resource efficiency, and nanomaterials can replace environmentally problematic chemicals in certain fields of application. High hopes are being placed in nano-technologically optimized products and processes for energy production and storage; these are currently in the development phase and are slated to contribute significantly to climate protection and solving our energy problems in the future.

In most commercially available "nano-consumer products", environmental protection is not the primary goal. Neither textiles with nanosilver to combat perspiration odor, nor especially stable golf clubs with CNTs, help protect the environment. Manufacturers often promise such advantages, typically without providing the relevant evidence. Examples include self-cleaning surface coatings or textiles with spot protection, with are advertized as reducing the cleaning effort and therefore saving energy, water and cleaning agents.

Emphasis is often placed on the sustainable potential of nanotechnology. Nonetheless, this usually reflects unsubstantiated expectations[7]. Determining the actual effects of a product on the environment – both positive and negative – requires examining the entire life cycle from production of the raw material to disposal at the end of the life cycle. As a rule, the descriptions of environmental benefits fail to consider the amount of resources and energy consumed in producing the products[3].

Life cycle assessment

A Life Cycle Assessment (LCA) is the appropriate approach to analyze and evaluate the sustainable benefits, ecological advantages or environmental impact of a product, a process or an application over its entire lifespan ("from the cradle to the grave"). Environmental impacts encompass all the environmentally relevant factors when extracting resources from the environment (e.g. raw materials such as ores or crude oil) as well as the emissions (e.g. wastes and CO_2). The term "life cycle assessment" is also used in a comparative sense, i.e. between several products.

The standardized regulatory framework of the "International Organization for Standardization" (ISO) is available (ISO 14040 and 14044) for an LCA. This encompasses the following elements: definition of the aim and investigation framework, life cycle inventory, impact assessment and evaluation. Compiling an LCA typically relies on special software.

LCAs focus on products and processes that are either already on the market or that are market ready. This enables using solid data. LCAs help analyze and evaluate potential health effects – to the extent that these can be described using impact models and that the relevant (epidemiological) data are available. Impact mechanisms of and exposures to nanomaterials, however, remain largely unknown. This means that health effects of nanomaterials still cannot be incorporated into an LCA at the present time. An additional difficulty in compiling an LCA for "nano-products" is that information on a product's properties and ingredients is often lacking. Manufacturers often point to the proprietary nature of such data. Finally, the information available on application guidelines and disposal is also often inadequate[7]. Accordingly, the few LCAs conducted on products with nanomaterials fail to encompass

Environmental benefits are expected especially in the following areas (see also:[1; 3; 4; 5; 6]):

- **Reduced use of raw materials through miniaturization**
  - By reducing the thickness of coatings and decreasing the amounts of food additives or cosmetic ingredients.
- **Energy savings through weight reduction or through optimized function**
  - In the future, novel, nano-technologically optimized materials, for example plastics or metals with carbon nanotubes (CNTs), will make airplanes and vehicles lighter and therefore help reduce fuel consumption;
  - Novel lighting materials (OLED: organic light-emitting diodes) with nano-scale layers of plastic and organic pigments are being developed; their conversion rate from energy to light can apparently reach 50 % (compared with traditional light bulbs = 5 %);
  - Nano-scale carbon black has been added to modern automobile tires for some time now to reinforce the material and reduce rolling resistance, which leads to fuel savings of up to 10 %;
  - Self-cleaning or "easy-to-clean"-coatings, for example on glass, can help save energy and water in facility cleaning because such surfaces are easier to clean or need not be cleaned so often;
  - Nanotribological wear protection products as fuel or motor oil additives could reduce fuel consumption of vehicles and extend engine life;
  - Nanoparticles as flow agents allow plastics to be melted and cast at lower temperatures;
  - Nanoporous insulating materials in the construction business can help reduce the energy needed to heat and cool buildings.
- **Energy and environmental technology**
  - Various nanomaterials can improve the efficiency of photovoltaic facilities;
  - Novel dye solar cells ("Grätzel cells") with nano-scale semiconductor materials are currently under development; they mimic natural photosynthesis in green plants;
  - Plastics with CNTs as coatings on the rotor blades of wind turbines make these lighter and increase the energy yield;
  - Nano-technologically optimized lithium-ion batteries have an improved storage capacity as well as an increased lifespan and find use in electric vehicles for example;
  - Fuel cells with nano-scale ceramic materials for energy production are under development; their production requires less energy and resources;
  - Nanoporous membranes and filters with nanomaterials are used in water treatment and purification;
  - Nanoparticular iron compounds are used in groundwater remediation to remove chlorinated hydrocarbons;
  - The effectiveness of catalytic converters in vehicles can be increased by applying catalytically active precious metals in the nano-scale size range, and
  - nanoporous particle filters are being developed to reduce emissions in motor vehicles.
- **Replacement of hazardous materials**
  - Nanosilver can potentially be applied to replace hazardous biocides, for example in wood preservatives or paints;
  - Nanoceramic corrosion coatings for metals without toxic heavy metals (chromium, nickel), for example in household appliances or automobiles, can replace environmentally harmful or hazardous chromium (VI) layers and conventional phosphating;
  - Nano-scale titanium dioxide and silica can replace the environmentally damaging bromine in flame retardants;
  - Nanoparticular titanium dioxide as a mineral UV-filter in sunscreens is being considered as an alternative to organic filters, which are a health concern.
- **Energy and resource efficiency in the chemical industry**
  - Nanocatalysts can be used to increase the yield of chemical reactions and reduce the amount of environmentally damaging byproducts.

all stages of the life cycle[8], hindering a comprehensive analysis and evaluation of environmental impacts and health effects.

The available LCAs indicate that the environmental impacts of a "nano-product" lie mostly in the production phase or in the nano-scale raw materials used[9]. Thus, producing an antibacterial T-shirt with nanosilver creates considerably more environmental damage than a conventional T-shirt. This is because the production of nanosilver, depending on the method used, emits larger amounts of environmentally damaging greenhouse gases[10]. In a long-term operation scenario, the life cycle assessment of two solar processes to purify water, for example, showed a distinctly higher environmental impact of the photocatalytic process with nano-TiO_2 as opposed to the conventional approach. This was due to the high consumption of resources in producing the nano-scale titanium dioxide[11].

Several available LCAs, however, do show – for certain products – clearly reduced environmental impacts or energy and resource savings based on nanomaterial use or nano-technological processes (for an overview see[12]). Precious metals in nanoform in automobile catalytic converters can reduce the use of such metals by 50-95 %. Nano-coated anti-reflex glass increases the efficiency of solar collectors by up to 6 %; nano-paints for automobiles can be applied in thinner coats and reduce the emissions of volatile organic compounds by 65 %. Organic Light Emitting Diodes (OLED) in displays have a higher energy efficiency and require less materials than conventional displays[13]. Life cycle assessments have been conducted for two nanotechnology-based products designed for more durable and water-repellent coatings of surfaces (wood, glass). They confirmed an environmental benefit based on the reduced amount of material applied and the lower cleaning effort. Due to missing data, however, the assessments relied on a series of assumptions[7]. Plastic beverage bottles (PET) with nanocoatings, for example, were compared with aluminum cans and no-deposit glass bottles in a life cycle assessment. The results showed that the nano-PET-bottle created about one-third less greenhouse gases than the aluminum can: the environmental benefit compared with the no-deposit glass bottle was as high as 60 %[14].

Beyond an LCA, a prospective environmental balance can be conducted in order to predict the benefits of an application or a process that is only in the development stage. Nonetheless, a range of technical problems and challenges can appear before the specific application comes on the market: the actual environmental benefits often remain open (see also[13]).

The current situation

To date, no resounding successes of nanotechnology in solving our environmental and climate-related problems have been documented: not every "nano-product" is by definition environmentally friendly or sustainable. In particular, environmental organizations emphasize that the advantages and potentials touted by industry are often exaggerated and untested; in many cases it could take years, if ever, until any such benefits are realized[15]. In fact, the fear is that nanotechnology will further increase energy and environmental costs[16].

The production of nanomaterials today often still requires large amounts of energy, water and environmentally problematic chemicals such as solvents. Currently, one kilogram CNTs contains about 0.1 to 1 terajoules (TJ) of energy[17]. One TJ corresponds to the energy content of about 167 barrels of crude oil (about 26,550 liters)[16]. This makes CNTs one of the most energy-intensive materials known to mankind[17]. The high-tech production of nanomaterials based on carbon, such as fullerenes, carbon nanotubes and carbon nanofibers, remains very energy intensive: any potential environmental advantages – such as those through fuel savings due to lighter vehicle bodies – are currently negated[17; 18; 19]. High energy demand plays an important role especially when mass producing a product requires large amounts of a nanomaterial. In contrast, if only very small amounts are used, for example of CNTs to produce special plastic films, then environmental benefits exist[12]. Thus, in order to determine such benefits, any potential energy savings in using a nanomaterial-based product must be compared with the energy consumed during its production. This must be done on a case by case basis. Further advances and improvements in production processes raise hopes that energy consumption can be reduced in the future.

The efficiency of nano-solar panels currently still lies about 10 % below that of conventional silica panels[16]. Moreover, nanotechnology has contributed little to making vehicles and airplanes lighter and thus more fuel efficient. The prerequisites for an industrial mass production (production volumes, automation level, quality standards) have not been fulfilled, and the high demands on the material (e.g. durability, strength, safety) cannot yet be met at competitive prices[20]. The contribution of nanotechnology to reducing the greenhouse gas CO_2 appears to be minimal: a 2007 estimate predicted savings of about 200,000 t CO_2 up to the year 2010 by reducing motor vehicle weight and emissions as well as by building insulation. This would correspond to a mere 0.00027 % of global CO_2 emissions[21].

Conclusions

Based on their special properties, nanomaterials have the potential to make products or production processes more environmentally friendly. The focus lies mostly on energy and resource efficiency. Several consumer products that promise environmental advantages are already available, and certain applications have already been implemented in the industrial sector. Much is currently in the research and development stage, especially in the sectors energy and environmental technology. The high expectations for potential environmental benefits of nano-technologically optimized products are contrasted by fears that the high consumption of energy and resources in industrial-scale nanomaterial production will negate any potential advantages. Unfortunately, in most cases no comprehensive life cycle analyses are available to evaluate the actual environmental effects – both the potential advantages as well as the risks – during the entire lifespan of a product. Manufacturers are therefore called upon to provide the necessary evidence to support claims of environmental advantages or to provide the data required for analyses and evaluations. As in other cases of technological innovation, the focus in nanotechnology is primarily on the intended functions of the respective nanomaterials. Positive environmental effects are rarely the reason for using a nanomaterial, but such an influence is clearly a welcome side effect. Depending on the actual conditions, negative effects or no effects at all can occur. This calls for actively creating conditions under which positive effects can be realized.

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