

Nanotechnology and Sustainability: Benefits and Risks of Nanotechnology for Environmental Sustainability

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Abstract

The potential positive and negative effects of nanotechnology-based materials and devices on the environment are discussed in this article. It was found that nanotechnology delivers benefits in the areas of environmental sensing and detection, remediation and treatment and energy conservation. Novel nano-engineered technologies provide more sensitive and reliable air and water monitoring solutions with real time response capabilities. Nanotechnology designs cost-efficient, simple-to-use, and more effective treatment and remediation tools of benefit for the long-term sustainability of air, water and soil resources. It has contributed to energy conservation through the development and application of energy saving and renewable energy technologies. Along with its benefits, the potential risks of nanotechnology for the environment are also addressed in this article.

Kurzfassung

Das Potenzial positiver und negativer Effekte von nanotechnologisch-basierender Materialien und Pläne für die Umwelt wurden bereits diskutiert. Es wurde herausgefunden, dass Nanotechnologie Leistungen in den Gebieten der Umweltanalytik und Erkennung, Sanierung und Aufbereitung sowie Energieeinsparung fördert. In der Umweltüberwachung bieten neue nano-strukturierte Technologien empfindlichere und zuverlässigere Luft- und Wasserüberwachungslösungen mit Fähigkeiten von Reaktionen in Echtzeit. Nanomaterialien verbergen das Potenzial, die längerfristige Nachhaltigkeit von Luft-, Wasser- und Bodenressourcen durch Schaffung kosteneffizienter, einfacher und wirkungsvollerer Behandlungsmöglichkeiten und Sanierungswerkzeugen zu verbessern. Nanotechnologie hat gezeigt, dass sie zu Energieeinsparung durch die Entwicklung und Anwendung von energiesparender Technologie und Technologien für erneuerbare Energien beiträgt. Neben dem Nutzen der Nanotechnologie für Umweltsustainability, wird ebenfalls das potentielle Risiko für die Umwelt und die Gesundheit des Menschen angesprochen.

1 Introduction

1.1 Background

The recent growth of nanotechnology manufacturing has led to unprecedented research and development efforts in both the public and the private sectors. Globally, an increasing number of laboratories develop novel, nanometer-sized materials for applications ranging from large-scale industrial materials, to medical products and electronic components.

In contrast to the small size of nanoparticles (NPs), the scale of their application is tremendous. Nanotechnology influences virtually all industrial and public sectors, including healthcare, agriculture, transport, energy, materials, information and communication technologies.

Our present reliance on fossil fuels for energy production and transportation as well as the extensive pollution from industry have major impacts on the environment. Nanoscience holds promise to contribute to more effective pollution control and reduction through the development of novel and better environmental monitoring, treatment and remediation technologies. It also shows potential to aid energy resource conservation through improvements in the fields of energy saving and renewable energies.

Both the potential benefits and the risks, associated with the application of nanomaterials have been largely debated in recent years. In contrast to the dominating optimistic projections that nanotechnology will bring significant technological development and well-being to society, it is considered that exposure to certain NPs may cause environmental problems and/or do harm to human health.

1.2 Research Goals

The main goal of this article is to give an overview of the impact of nanotechnology on the environment. In order to achieve the goal, the following research questions were investigated:

1. What are the benefits of nanotechnology for the environmental sustainability?
2. What is the current state of knowledge of the risks of nanomaterials for the environment?

1.3 Methodology

This article is based on an extensive review of literature published in the period: 01/2001-08/2009. The selected literature was mainly in the form of scientific papers, but also books, information from conferences and patent data were used.

2 Benefits of Nanotechnology for the Environment

In 2003, Masciangioli and Zhang divided the benefits of nanotechnology for the environment into three categories: sensing and detection, remediation and treatment and pollution prevention (MASCANGIOLI and ZHANG, 2003). Some other important benefits were identified at the European Commission Nanoforum Workshop (ECNW) in 2006: energy and material conservation (ECNW, 2006).

2.1 Environmental Monitoring and Sensing

Environmental monitoring plays an important role in natural and resource conservation. It is crucial for environmental policy and research, because it provides policy makers, scientists and the public with the data, needed to understand and improve the environment.

2.1.1 Air Monitoring

Conventional air pollution monitoring employs large, fixed systems, which often fail to detect local "hot spot" pollution peaks (RICKERBY & MORRISON, 2006). Solid-state gas sensors (SGSs), based on nanocrystalline metal oxide thin films, provide faster response with real-time analysis capability, higher resolution, simplified operation and lower running costs, compared to conventional methods, such as chemiluminescence and infra-red spectrometry (RICKERBY & MORRISON, 2006).

SGSs are traditionally made of one or more metal oxides of the transition metals – tin, zinc, aluminum, etc. Today, NPs and thin films of metal oxides (< 100 nm thick) are used to construct the sensors. The advantages of using nanomaterials in the construction of the SGSs are: (1) higher sensitivity, (2) better selectivity and (3) shorter response time of the devices (RICKERBY & MORRISON, 2006). The sensitivity and selectivity of SGSs depend on their operating temperature, the film thickness, porosity and the particle size of the building material (RIUS et al., 2007). For the same chemical composition, the smaller the NPs, building the semiconductor are, the more sensitive the sensor is (RIUS et al., 2007). The reason behind this is that semi-conducting materials built of smaller particles have vaster active surface areas and they are ab-

le to absorb more gas molecules, which lets the system faster and easier identify the fluids. Tin, indium, zinc or tungsten oxides, synthesized in the form of nanowires, nanobelts and nanocombs are tested today. These morphologies significantly increase the effective surface area of the semiconducting material (and the sensitivity of the sensor devices, respectively) and they will soon be integrated into the next generation of SGSs.

The nano-fabricated SGSs are very flexible to use due to their light weight and small size, which make them appropriate to be fitted anywhere. By binding the sensors to a global positioning system (GPS) and connecting them via an intelligent sensor network, data can be transferred from remote locations to a central service site, where it can be modelled using Geographic Information System (GIS) software (REICHEL, 2005). The modelled data can be easily distributed via internet and made accessible to everyone.

2.1.2 Water Monitoring

When the EU Water Framework Directive was implemented in 2000, new regulations for water monitoring of organic substances were imposed and measurements had to be done down to microgram-per-litre ($\mu\text{g l}^{-1}$) levels. Such accuracy, however, was difficult to achieve with conventional water monitoring technologies and a necessity for faster, more sensitive systems appeared. This is how the Automated Water Analyzer Computer Supported System (AWACSS) was created.

AWACSS was a joint project among researchers from Corporate Technology in Erlangen, the University of Tübingen, the Water Technology Center in Karlsruhe and other partners. The project was financed by the European Commission (EC) and technically designed by Siemens. AWACSS has the size of a suitcase and it can simultaneously test several samples and send the results to a central server. The device utilises an integrated optical nanochip and it uses an immunoassay technique to selectively capture the contaminant molecules. The system is able, within less than 18 minutes, to check for 32 different substances, ranging from antibiotics and pesticides to hormones and detect even tiny concentrations of less than $1 \mu\text{g l}^{-1}$ (PROLL and GAUGLITZ, 2006).

2.2 Remediation and Treatment

A major benefit of nanotechnology for the environment is the development of remediation and end-of-pipe treatment technologies. Some of the advantages they offer over conventional technologies are (1) better selectivity and (2) ability to remove even the finest contaminants from water and air.

2.2.1 Remediation

Nanoscale zero-valent iron (nZVI) is an important example of water remediation nanotechnology for *in situ* application. nZVI particles effectively remove a wide variety of common environmental contaminants, including heavy metals, pesticides, chlorinated organic solvents, volatile organic compounds (VOCs) etc. (ZHANG, 2003).

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Nano-particulate titanium dioxide (TiO₂) has been traditionally used in environmental remediation because of its low toxicity, high photoconductivity, high photostability, availability and low cost (NAGAVENI, 2004; WALINGTON, 2005). Novel technologies and improved processes, however, enabled the development of a variety of TiO₂ photocatalytic derivatives. Metals such as copper (Cu), silver (Ag), gold (Au) and platinum (Pt) have been tested for their ability to improve the decontamination activity of TiO₂ NPs. Coating TiO₂ with Cu, for example, accelerates the reduction of hexavalent chromium (Cr (VI)) ions (RAJESHWAR, 2001). The coupling of TiO₂ with Au or Ag results in similar reductive capabilities.

The TiO₂-based p-n junction nanotubes (NTs) represent the most recent innovation in the field of nanophotocatalysts. The NTs contain platinum (Pt) (inside) and TiO₂ (on the outside). The TiO₂ coating of the tube acts as an oxidizing surface, while the inside of the tube is reductive (CHEN et al., 2005). The ability of the p-n junction NTs to destroy toluene was tested by Chen et al. and the results showed that they exhibit much higher decontamination rates than non-nanotube materials (CHEN et al., 2005).

A wide variety of nano-remedial tools are currently tested on the bench scale. Some important examples are included in the following table.

Table 1:

Groundwater remediation nanotechnologies. All¹ – Inorganic contaminants: Heavy Metals, Nitrites (NO₂), Salts, Asbestos, Radionuclides, Calcium (Ca), Magnesium (Mg), etc.; All² – Organic contaminants: Pesticides, Herb- & Insecticides, Industrial Effluents, MTBE, PAHS, PCBs, VOCs, etc.; All³ – Biological contaminants: Bacteria, Bacterial Spores, Giardia & Cryptosporidium, Cysts, Coliform, Fecal Coliform, DNA & RNA, Fungi, Mold, Parasites, Protozoa, and Viruses

Type of Technology	Contaminants Removed		
	Inorganic	Organic	Biological
Applied on the large scale			
nZVI	Arsenic (As), Mercury (Hg), Nickel (Ni), Nitrates (NO ₃), Ag, Radioactive Metals etc.	All ²	No
Nanoscale (TiO ₂)	As	All ²	All ³
Nanoscale zinc dioxide (ZnO ₂)	Unspecified	Chlorinated phenols, Halogenated hydrocarbons (HHCs)	All ³
Applied on the bench scale			
Ferritin-encapsulated iron oxides	Cr (VI)	Aromatics, Chlorocarbons	No
Polymeric NPs	No	Hydrophobic organic contaminants (HOCs), Polynuclear aromatic hydrocarbons (PAHs)	No
Dendrimers	Heavy metals, Cu	Unspecified	Unspecified
Single-enzyme NPs	Dep. on enzyme	Dep. on enzyme	Dep. on enzyme

2.2.2 Treatment

Nanofiltration is a relatively recent membrane filtration process, which holds promise to deliver cost effective water and air treatment solutions. Nanomembranes (NMs) are used not only to remove contaminants from polluted water and air, but also for desalination of salty water. There are two types of NMs, currently available on the market: nanofilters, using either carbon nanotubes (CNTs) or nanocapillary arrays to mechanically remove impurities; and reactive NMs, where functionalized NPs chemically convert the contaminants into safe byproducts.

Ordered arrays of densely packed, vertically aligned CNTs are used as membranes to filter out water impurities, while letting the water flow freely through the filters. Carbon Nanotube Membranes (CNMs) are able to remove almost all kinds of contaminants, including bacteria, viruses, and organic pollutants. CNMs are also effective in desalinating salty water. (MERIDIAN INSTITUTE, 2005)

Until now, several NM types, which effectively remove CO₂ from industrial flue gases, were developed from both polymeric and inorganic materials (i.e., carbon-based membranes, mesoporous oxide membranes and zeolite membranes). These membranes show better selectivity and higher removal capacity than their conventional alternatives and they are often more cost-efficient (FUJIOKA et al., 2007). The large scale industrial application of the CO₂-removing NMs would contribute to the reduction of the anthropogenic CO₂ emissions in the atmosphere and impede Climate Change.

The U.S. Pacific Northwest National Laboratory (PNNL) developed the Self Assembled Monolayers on Mesoporous Supports (SAMMS). SAMMS are a combination of mesoporous ceramics (with pore diameters between 2 and 50 nm) and self-assembled chemical monolayers. Both the monolayer and the mesoporous support can be functionalized to remove specific contaminants (e.g., Hg, Cd) (WALINGTON, 2005). SAMMS exhibit faster adsorption, higher removal capacity, and better selectivity than many other membrane and sorbent technologies. The reason behind the rapid kinetics is attributed to the rigid, open pore structure of SAMMS, which leaves all of the binding sites available at all times to bind contaminant molecules (PNNL, 2008).

A variety of SAMMS types exist today. The most famous material is the thiol-SAMMS. Other important materials are the ethylenediamine (EDA) – SAMMS, the phosphonate-, hydroxypyridone- and the chelate-SAMMS. SAMMS can be assembled into filters and used for the filtration of water and other liquids. SAMMS types for a great variety of contaminants can be designed.

2.3 Nanotechnology and Energy

Nanotechnology has been shown to directly contribute to the long term energy sustainability through the development of energy saving and renewable energy technologies.

2.3.1 Energy Saving

In the context of sustainability, energy saving has two-fold advantage – it directly translates into conservation of non-renewable energy resources and into pollution abatement. Nanotechnology has contributed to energy saving in several respects: more effective temperature control (thermal insulation) materials, lighter and stronger materials for vehicle production, more efficient lighting devices and fuel cells.

Nanoscience led to the development of a variety of ultra low-density, transparent, aerogels with better insulating properties. Today, these materials can be applied in superinsulating windows, skylights or specialty windows. In addition, low cost, spectrally sensitive nanothin film coatings were developed in recent years, which, when incorporated in glass, can reduce glare and light passing through windows and control the thermal exchange across them (MALSCH, 2004).

The development of lighter and stronger materials for vehicle manufacturing is an important benefit for energy saving. Automobiles, trains, planes, ships and other means of transportation use less energy per distance if they are constructed of lighter materials and thus they emit less pollutants and save energy. Lighter materials, being used in vehicles, can be plastics, reinforced with NPs to become stronger per weight unit and lighter or nanocrystalline ceramic composites such as zirconium (Zr), silicon nitride (Si_3N_4) and silicon carbide (SiC) in alloys, which can make alloys lightweight, mechanically stronger and chemically more resistant. Metal matrix composites (MMCs) are another group of materials, which are usually lighter than their respective alloys. When embedded with NPs, MMCs can deliver qualities such as self-lubrication, abrasion-resistance and energy-absorbing capabilities (CALLISTER, 2007).

Nanotechnology has taken major part in improving the Light-emitting Diode (LED) technology through the invention of the Quantum Dot (QD) LEDs, the Quantum-Caged Atoms (QCA) and the Organic LEDs (OLEDs). The LED technology enables the production of light bulbs, which last for years and consume less than half of the energy, used by conventional lighting. In addition, OLEDs are already used for the design of displays, which use much more energy efficient than the Liquid Crystal Displays (LCDs). The OLED displays are thinner, flexible (can be folded) and they use less energy, which saves costs. These are solid benefits, which make them more attractive for the customers and they may soon replace the LCD displays on the market. The mass utilization of OLED displays and LED lightning devices will result in significant energy savings.

2.3.2 Renewable Energy Technologies

Nanotechnology has been shown to contribute to energy efficiency and pollution abatement through advancements in the area of renewable energy technologies.

Solar Photovoltaics (PV) for electricity production is the field, the development of which is most dependent on nanoscience. Research in PV is done in two main directions – to reduce solar cells manufacturing costs of and to increase their energy conversion efficiency. Until now nanotechnology has shown limited potential to

increase the PV cell efficiency, but it has shown promising results in reducing their manufacturing and installation costs. There are several PV technologies on the market today, developed with the aid of nanotechnology-Crystalline and Amorphous Thin-film Solar Cells, Cadmium Telluride (Cd/Te) Composite Nanocrystal Cells, Copper Indium Gallium Selenide (CIGS) Thin-film Cells, Organic Grätzel Cells and Polymer Solar Cells.

The Thin-film Copper Indium Gallium Selenide (CIGS) technology is considered most promising among the nano-PV technologies. CIGS cells show high efficiency ($\approx 18-20$) compared to conventional silicon multicrystalline technology ($\approx 19-22$) and their manufacturing costs are lower (GREEN et al. 2009). The continuous research, carried out by several companies (i.e., Shell Solar, IBM, Global Solar Energy, Nanosolar), is expected to further cut costs and increase cell conversion efficiency.

The Grätzel solar cells, also known as Dye Sensitized Cells (DSCs), are produced using cheap materials and simple, low energy processes, which make the technology environmentally friendly and relatively inexpensive (GRÄTZEL, 2007). DSCs use photo-electrochemistry to extract energy from light. The technology is clean and sustainable and it already has practical applications for solar energy conversion and photocatalytic water treatment. At the current stage of development, however, the Grätzel technology still exhibits much lower conversion efficiency ($\approx 9-10$) than silicon crystalline technology ($\approx 19-22$) (GREEN et al. 2009).

Polymer solar cells are relatively easy to manufacture and their cost is less than one-third of that of traditional silicon solar cells, because the polymers and fullerenes used in their production are available and inexpensive. Compared to conventional silicon cells, polymer solar cells are lightweight, disposable, inexpensive to fabricate and flexible to install (DYAKONOV et al., 2003, OOSTERHOUT et al., 2009). Unfortunately, at this stage of development polymer solar cells can hardly compete with conventional silicon cells because of their low conversion efficiency (≈ 8) (GREEN et al., 2009). In addition, polymer solar cells can suffer considerable degradation – their efficiency is decreased over time due to environmental degradation, caused by water, oxygen and UV rays.

However, because of the enormous potential polymer solar cells technology has in terms of cost and flexibility of installation, researchers work on making it commercially attractive. A novel vinylidene chloride- and acrylonitrile-based polymer nanotube composite, which can significantly improve the lifetime of organic PV devices, was recently introduced by researchers from the Forest University in North Carolina, USA (RAVICHANDRAN et al., 2008).

3 Risks of Engineered Nanoparticles (ENPs) for the Environment

Along with the expected benefits of nanotechnology, it is important to recognize that it is still a largely unknown area and the conse-

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quences which can follow the widespread utilization of nanomaterials are difficult to predict. It is possible that nanotechnology leads to novel environmental problems, posing hazards for the environment and human health.

Several important aspects in regard to the environmental risk assessment (ERA) of ENPs are addressed in this section: physico-chemical properties identification and characterization, environmental fate and ecotoxicity.

3.1 Chemical Identification and Physical Properties Characterization of ENPs

Developing understanding about the physical and chemical properties of substances and materials is a fundamental step in their ERA. It is expected that the environmental impacts of ENPs will not be based solely on their standard physicochemical properties such as composition, structure, molecular weight, melting point, boiling point, vapour pressure etc., but also on the novel properties they exhibit. This makes the characterization of ENPs very difficult.

The following table shows the number of studies in the fields of identification and characterization of ENPs, done between 2004 and 2009. These studies were selected and evaluated by AITKEN et al. (2009).

Table 2:

A summary of studies on the metrology, identification and characterisation of ENPs and their total funding value (modified after AITKEN et al., 2009)

Specific Research Field		State of Progress			
		Unknown	In Progress	Completed	Total
Identification of metrics and associated methods for the measurement of ENPs	Number of Studies	4	12	12	28
	Funding Value (mill. €)	-	16.23	6.80	23.02
Development of standardised, well-characterised reference ENPs	Number of Studies	1	1	6	8
	Funding Value (mill. €)	-	0.28	0.20	0.47
Understanding the properties of ENPs in the context of their ignition and explosion potential Number of Studies	Number of Studies	0	1	2	3
	Funding Value (mill. €)	-	5.57	0.32	5.89

As it can be inferred from table 2, most of the current research on the properties of ENPs is focused on the identification of metrics and associated measurement methods. This type of research is fundamental in the sense that without reliable measurement methods it would be difficult to develop good understanding of the physical

and chemical characteristics of the ENPs. Only few comprehensive studies on the characterization and standardization of ENPs have been published so far. Deficiencies in the NP characterization data impact each of the four steps of the ERA procedure, when it is applied to ENPs (i.e., hazard identification, dose-response assessment, exposure assessment and risk characterization) and makes it very difficult to assess their risks for the environment. The chemical regulation policies of the EU, USA and many other countries are based on the risk assessment approach. Basically, no characterization of ENPs means no risk assessment of ENPs, which results in no regulation of ENPs. The latter puts the environment and society under substantial risks of problems due to NP pollution.

3.2 Ecotoxicity of ENPs

Nanomaterials are expected to affect living organisms in a different way than larger particles of the same materials. Since ENPs differ greatly from each other in their structure and properties, it is expected that they would differ also a lot in terms of toxicity. Only a few ecotoxicity studies with ENPs were completed till 2004. The following table gives an overview of the number of ecotoxicity studies with ENPs in the period 2004-2009.

Table 3:

A summary of studies on the ecotoxicity of ENPs (2004-2009) and their total funding value (modified after AITKEN et al., 2009)

Specific Research Field		State of Progress			
		Unknown	In Progress	Completed	Total
Research to establish the uptake, toxicity and effects of ENPs on surface water, groundwater and soil microorganisms, animals and plants	Number of Studies	6	14	23	43
	Funding Value (mill. €)	0.28	2.18	4.00	6.46
Research to establish the mechanisms of toxicity, toxicokinetics and in vivo effects of ENPs to key ecological groups (including invertebrates, vertebrates (e.g., fish) and plants)	Number of Studies	3	4	15	22
	Funding Value (mill. €)	0.15	0.81	1.86	2.82
Define endpoints to be measured in ecotoxicological studies and assess the feasibility of the standard tests for persistence, bioaccumulation and toxicity for the purpose of applying them to ENPs	Number of Studies	1	8	3	12
	Funding Value (mill. €)	-	4.70	0.80	5.48

Research studies, focused on the uptake, toxicity and effects of ENPs on water and soil organisms brought information about the toxicity of some ENPs (i.e., functionalised quantum dots, zero-valent iron NPs). The studies in the mechanisms of toxicity, toxicokinetics and in vivo effects of ENPs to key ecological groups delivered some improvement to the understanding of the kinetics of nanoparticle uptake in invertebrate and vertebrate models and its relation to toxicity (AITKEN et al., 2009). In addition, a number of studies focussing on microbial organisms provided information, relevant to effect assessment at both individual and community levels. The studies, however, only cover a limited range of species and material types. Research on the mechanisms of toxicity in plants appears to be very scarce, which is a severe gap in knowledge. It is still unclear to what extent the current standard tests for persistence, bioaccumulation and toxicity are applicable to ENPs (AITKEN et al., 2009).

3.3 Environmental Fate of ENPs

Since a very limited number of studies are done on environmental fates of ENPs, it is still unknown how most of them would behave in the environment. It is very important to thoroughly study the environmental fate of ENPs. This would make it possible to determine their behaviour and residence times in the different environmental media. There is a linear dependence between residence time and the probability for uptake by living organisms, bioaccumulation and possible intoxication.

Developing understanding about the environmental fates of ENPs is fundamental for their environmental exposure assessment, as part of their risk assessment. It is essential to gain this kind of knowledge in order to make ERA of ENPs possible.

Table 4:

A summary of studies on the environmental fate of ENPs and their total funding value in the period 2004-2009 (modified after AITKEN et al., 2009)

Specific Research Field		State of Progress			
		Unknown	In Progress	Completed	Total
Understanding the environmental fate, behaviour and interaction of nanoparticles in air	Number of Studies		7	5	12
	Funding Value (mill. €)	-	1.42	2.20	3.62
Understanding the environmental fate, behaviour and interaction of nanoparticles in soils and water	Number of Studies		13	23	36
	Funding Value (mill. €)	-	1.74	5.09	6.83

4 Conclusions and Recommendations

4.1 Benefits of Nanotechnology for Environmental Sustainability

It has been concluded that nanotechnology delivers benefits for Environmental Sustainability in the areas of environmental sensing and detection, remediation and treatment and energy conservation.

4.1.1 Environmental Monitoring

In environmental sensing and detection, novel nano-engineered technologies provide more sensitive and reliable air and water monitoring solutions. The nano-units integrated in the sensors, significantly increase the sensitivity of the devices. In addition, the small size of the nano-sensors delivers significant flexibility of application. It makes it possible to assemble them into flexible, mobile, real time monitoring systems, easy to reconfigure and apply on different spacial scales, providing high quality, reliable air quality measurement data.

4.1.2 Remediation and Treatment

Remediation nanotechnologies are different from each other in the way they remove contaminants from the environment. Some of them use chemical conversion mechanisms like oxidation and reduction, while others act as catalysts. Despite the differences, however, the effective operation of most depends on the effective surface area of their active materials. The large surface areas of NPs make them more effective for the removal of contaminants than their macro-sized alternatives and thus preferred for environmental remediation.

Nanotechnology has led to the development of a variety of water and gas end-of-pipe treatment technologies. Many of these technologies are still on the bench scale, but some (e.g., CNMs) are already available and competitive on the market. In the context of the global water shortage problem, technologies such as the CNMs are important breakthroughs with potential to become widely used and, thus, deliver substantial water treatment benefits.

It is expected that nanomembrane technology will deliver in the very near future powerful, cost effective solutions for the effective removal of CO₂ from flue gases (i.e., highly selective carbon nanotube, polymeric and zeolite membranes). When applied in industry, these technologies may become a valuable ally in the combat against Anthropogenic Global Warming.

4.1.3 Energy Conservation

Nanotechnology has been shown to contribute to energy conservation through the development and application of energy saving and renewable energy technologies. Nanoscience accounts for the development of a vast variety of high-performance materials for thermal insulation as well as of lighter and stronger materials for vehicle production and LEDs for application in energy efficient lightning devises and displays. In the field of renewable energy, nanotechnology has contributed to the development of a variety of solar photovoltaic (PV) technologies for electricity production. PV

nanotechnologies have lower production costs than the expensive, conventional silicon crystalline technology, but unfortunately, at this stage of technological development, they still show lower energy conversion efficiency. The Thin-film Copper Indium-Gallium Diselenide (CIGS) technology is considered as the most promising PV nanotechnology. CIGS cells show very high conversion efficiency compared to the rest of the nano-PV technologies and their manufacturing costs are relatively low.

4.2 Risks of Nanotechnology for the Environment

It is impossible at that point of time and stage of knowledge to make any collective judgment about the potential risks of nanotechnology for the environment. ENPs are expected to affect living organisms in different ways than larger particles of the same materials. Since they differ greatly from each other in terms of structure and properties, it is expected that they would differ also a lot in terms of toxicity. Only a limited number of ecotoxicity studies with ENPs have been conducted so far and the data they delivered is insufficient to characterize hazard. The environmental fates of ENPs are still not well studied and it is still uncertain how most ENPs would behave in the environment. It is essential to do more research in the fields of property characterization, environmental behaviour as well as more ecotoxicity studies in order to make ERA of ENPs possible. Being unaware of the potential risks, associated with ENPs would prevent policy makers from imposing adequate regulation of ENP-containing materials. The lack of regulation can lead to widespread exposure to dangerous ENPs which can cause substantial environmental and social problems.

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