Für Mensch & Umwelt

Umwelt Bundesamt

4 December 2015

Factsheet

Use of nanomaterials and nanoscale products for wastewater treatment

1. Introduction

Healthy stay requires care. One of the foundations of this is a healthy environment which is not burdened us with pathogens and pollutants - neither in the air nor via food. (Drinking) water is our most important foodstuff, but also much more: it is quite simply essential for supporting all life. Access to clean (drinking) water was declared a human right by the UN General Assembly in 2010. In addition, the European Water Framework Directive (Directive 2000/60/EC) states that "Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such".

The treatment of contaminated water prior to its introduction into surface water is one of the most pressing global challenges of the future. Existing processes for treating water and wastewater can be optimized by suitable nanotechnology applications, which can result in a more targeted removal of contaminants, better energy efficiency and lower costs. Experts predict that the water sector, as well as the energy sector, could also benefit most from innovative nanotechnology applications in the medium to long term (Bachmann et al. 2007). In addition to the benefits of using nanomaterials for water treatment, it should also be borne in mind that nanomaterials can have unintended impacts on the environment and human health. When using nanomaterials it is important to note that the novel properties of nanomaterials may possibly also have harmful effects on the environment and humans.

It must be ensured in advance of the applications that the nanomaterials are firmly integrated in the respective matrices so that they cannot enter the treated wastewater and bodies of water (Riegel et al. 2013). To date, not enough is known about the behavior and effects of nanomaterials, if they enter surface waters and, ultimately, drinking water via the treated wastewater (see 3.2 Potential impacts on the environment and health).

Catalytic and adsorptive treatment processes using nanoporous membranes[1] are therefore now used, for example, in water treatment, in order to eliminate undesired odor and water ingredients (such as micropollutants, pollutant burdens) or for "disinfection" purposes

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[1] Nanoporous materials have a large specific surface area on which substances which have to be filtered out can accumulate. In addition, they have a high reactivity which increases the adsorption and/or their catalytic effect.

(reduction of pathogens). Most approaches to nanotechnological application are currently still at the prototype or basic research stage. It is not yet possible to make any statements about the suitability and large-scale implementation at this stage of development.

2. Nanomaterials[2] and nanotechnological applications in wastewater treatment

Nanomaterials have properties which change continuously (e.g. solution kinetics, sorption) or intermittently (e.g. superparamagnetism) with their size. As a result, this enables the development of new high-tech materials for efficient water treatment processes such as filter membranes, nanocatalysts, functionalized surfaces, coatings and reagents. The material and energy consumption for treating water can therefore be reduced, if required, which can lead to a reduction in the costs of water and wastewater treatment in the long term.

The following table lists the usual nanomaterials and nanostructured materials[3] for different applications and technologies, as well as the advantages and disadvantages of these (Qu et al. 2013a and 2013b; Bora and Dutta 2014; Amin et al. 2014; Gehrke et al. 2014). Possible adverse effects on the environment and human health have therefore not yet been sufficiently and conclusively clarified (see Section 3). It has not yet been clarified in all cases whether and to what extent the materials and applications are cheaper and result in a reduction in environmental impact, because they are still in a developmental stage.

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[2] Nanomaterials consist of definable structural components with a size range of 1 - 100 nanometers (1 nm = 10^{-9} m) in at least one dimension (see also the Commission’s recommendation of 18.10.2011 for the definition of nanomaterials (2011/696/EU). Both natural and anthropogenic nanomaterials occur in the environment. Technically produced nanomaterials are used in nanotechnology.

[3] Nanostructured materials are materials having an internal nanostructure or a surface nanostructure, where the nanostructure is therefore an integral part of a larger object. Nanostructured materials are, for example, nanostructured powders or nanocomposites composed of nano-objects (Walz, A., Völker, C. and Klöppel, L. (2014) Nanotechnologie: eine Übersicht. Vorarbeiten zu einer sozial-ökologischen Risikoforschung., ISOE-Materials Soziale Ökologie, Nr. 39. Frankfurt am Main).

Table: Current and potential applications of nanotechnology in water and wastewater treatment

Nanomaterials	Technical properties		Application	
	desired	not desired		
Carbon nanotubes (including modified ones)	- very good sorption, - bactericide, - reusable	- high production costs	- poorly degradable pollutants (pharmaceuticals, antibiotics) disinfection, very high specific salt adsorption by ultra long carbon nanotubes	*in development*
Polymeric nanoadsorbents (dendrimers)	- Bifunctional removal of heavy metals and organic compounds (inner shell adsorbs organic substances, outer branches adsorb heavy metals), - reusable, - controlled release of nanosilver, bactericide		- removal of organic substances and heavy metals	*in development*
Nanostructured adsorbents (e.g. zeolites)	- high specific surface area		- all areas of water treatment	*in use*
Nanosilver	- bactericide	-not reusable	- water disinfection, antiblocking agent	*in development*
Nano-TiO_2	- high chemical resistance, - very long life - photocatalytic activity	-requires UV activation -slow reaction	- water disinfection, antiblocking agent, decontamination of organic compounds, disinfection (e.g. iron (II) and iron (III) oxide)	*in development*
Magnetic nanomaterials (e.g. iron (II) and iron (III) oxide)	- slight recovery by a magnetic field	- chemical stabilization required	- removal of heavy metals (arsenic) and radionuclides, filter medium, suspension reactors, powder, pellet - groundwater sanitation	*in use*
nanoscale Zero-Valent Iron (nZVI)	- high reactivity	- chemical stabilization required (surface modification)	- groundwater remediation (chlorinated hydrocarbons, perchlorates)	*in use*

Nanomaterials	Technical properties		Application	
	desired	not desired		
Filtration membranes[4]	- charge-based repulsion reduces blocking, relatively low pressure necessary, high selectivity		- reduction of hardness, color, odor, heavy metal concentration	*in use*
Composite membranes		resistant basic material is required, possibly release of nanomaterials	- extremely dependent on the composite material e.g. reverse osmosis, biological nanocomposite membranes	*in development*
Nanoporous membranes	- homogeneous nanoporous, - customized membranes	- low availability - (laboratory scale)	- ultrafiltration	*in use*
Nanofiber membranes	- high porosity, customized - higher permeate efficiency	- pore blocking, - release of nanofibers possible	- filter cartridge, ultrafiltration, prefiltration, water treatment, independent filter device	*in use*
			- composite nanofiber membranes, biological nanofiber membranes	*in development*
Aquaporin-based membranes	- high ionic selectivity and permeability	- mechanical weakness	- low-pressure water desalination	*in development*
Nano zeolites	- high porosity, hydrophilicity - high permeability of the thin layer nanocomposite membranes		- all areas of water treatment	*in use*

Different possible methods for wastewater treatment using nanomaterial and/or nanotechnologies are presented below (Qu et al. 2013a and 2013b; Bora and Dutta 2014; Amin et al. 2014; Gehrke et al. 2014). Nanomaterials are also used during water testing and monitoring of water treatment, and during sample enrichment and detection.

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[4] These membranes are, whose properties been modified by nanomaterials

2.1. Adsorption

Adsorption is a method for removing organic and inorganic pollutants from water and wastewater. Adsorption is defined by the surface structure of the adsorbing material, and by the presence of functional groups. These properties determine the selectivity and adsorption kinetics. Adsorbents made of nanomaterials and nanostructured materials have very high specific surface areas, possibly combined with functional groups, low diffusion distances, definable pore sizes and surface chemistry. They can be easily integrated into existing treatment steps in suspension reactors or adsorbers. The adsorbents have to be separated from the system following the completion of the treatment process, which is not always possible with nanomaterials or which is associated with a higher outlay. A distinction is made between carbon-based adsorbents, metal oxide-based adsorbents and polymeric adsorbents.

Initial investigations show that carbon nanotubes (CNT) can be used for special applications, because they can be modified in a customized way, thus e.g. for the adsorption of tetracycline (an antibiotic) (Ji et al. 2009). They can also be used for the adsorption of heavy metals. However, CNT are not a good alternative to the use of activated carbon as broad-spectrum adsorbents, since CNT have a relatively low adsorption capacity with respect to low molecular weight polar compounds and are only suitable for the targeted removal of individual critical and persistent pollutants.

Nanoscale metal oxides such as iron oxides (Fe_xO_Y e.g. Fe_3O_4, FeO(OH), titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3) are efficient and cost-effective adsorbents for radionuclides and heavy metals such as arsenic, lead, mercury, copper, cadmium, chromium and nickel. Sorption takes place mainly through complex formation between dissolved metals and the oxygen in the metal oxides. The capacity of the adsorbent depends on its specific surface area. Changes in the surface structure, e.g. due to nanostructuring, create larger surface areas for adsorption. In addition to their high adsorption capacity, iron oxide nanomaterials are also magnetic. As a result, they can be removed “completely” from the treated water with the adsorbed substances by means of magnetic separation. Test results regarding the removal of a variety of heavy metals have been promising, particularly those regarding the removal of arsenic (Bartsch et al. 2005).

The good adsorptive properties of activated carbon with respect to organic and inorganic pollutants are particularly limited with respect to arsenic. The adsorption capacity can be increased with respect to arsenic and other substances which are difficult to adsorb by impregnating activated carbon or other porous materials with nanoscale metal (hydr)oxides.

An important aspect regarding the cost effectiveness of these adsorbents is the possibility of regenerability and, thus, their reuse and metal recovery, which is generally greater than 90% (Qu et al. 2013). In some cases, it has been possible to achieve more than 100 regeneration cycles.

Dendrimers[5] are customized polymeric nanoscale adsorbents. They are able to adsorb both organic and metallic compounds (including heavy metals, copper) (Diallo et al. 2005).

2.2. Nanostructured membranes and membrane processes

Nanostructured membranes include, in particular, nanofiber membranes, composite membranes, biomembranes and special membranes for forward osmosis[6].

Nanofibers have a high specific surface area and porosity and can be adapted to different applications due to their special properties. Commercially, they are already used for air filtration; their use for wastewater treatment is still being explored.

Nanofibers are produced by the so-called process of electrospinning. Extremely fine fibers made of various materials (e.g. polymers, ceramics, metals) can be produced with this process (Cloete et al. 2010). In addition, functional nanomaterials can be integrated into the fibers, so that multifunctional media/membrane filters can be manufactured for particular problems.

Nanofiber membranes have a high flow rate and can remove pollutants, bacteria, viruses and proteins from the liquid phase by means of electrostatic effects. Their potential area of application could therefore be the preliminary treatment of the water or wastewater prior to ultrafiltration or reverse osmosis[7]. This can result in an extension of the life of the reverse osmosis membranes. In addition, the removal of heavy metals and organic pollutants can be favored during filtration.

Composite membranes consist of a material which is manufactured from two or more interconnected materials. It has different material properties to its individual components. The material properties and the structure of the components are of importance for the properties of the composite materials. Nanocomposites consist of nanoscale fillers which are introduced into a matrix. They frequently have a higher performance than conventional composite materials. This is achieved by the large surface area of the nanoscale fillers, through which these increasingly interact with the matrix material. In addition, the nanoscale fillers are homogeneously distributed in the matrix material. Hydrophilic metal oxide (e.g. Al_2O_3, TiO_2 and zeolite), antimicrobial (e.g. Ag and CNT) and (photo) catalytic (bimetallic, TiO_2) nanomaterials can, for example, be integrated into the membranes. The integrated nanomaterials improve the properties of the membranes such as water permeability, reduction of

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[5] These are specially manufactured organic compounds having a tree-shaped structure (in Greek dendron = tree).

[6] In forward osmosis two fluids with different osmotic pressures are brought into contact by means of a semipermeable membrane. As a result, water is transported into the cell with the higher osmotic pressure and the dissolved components are retained.

[7] Reverse osmosis is a process for concentrating dissolved solids in liquids, where the osmotic process across a membrane is reversed by applying a pressure.

contamination (e.g. by preventing the growth of biofilms) and increased stability.

Many natural membranes are very selective and permeable due to special pore-forming proteins, so-called aquaporins. These can be incorporated into commercially available nanofiltration membranes. Currently, there is no such membrane which can permanently withstand the operating pressures of reverse osmosis, the harsh cleaning conditions (high temperature, acid and alkaline cleaning agents) and fouling-based corrosion (Gehrke et al. 2014).

Forward osmosis requires special membranes. Such membranes are manufactured from different materials and are modified with nanomaterials (e.g. nano-magnetite, nano-copper). Forward osmosis has important advantages compared with pressure-driven reverse osmosis: it does not require a high pressure, the membrane is less susceptible to contamination and, in addition, the energy consumption decreases.

Specific practical applications in the field of water and wastewater treatment are nanoscale filter systems and nanoporous membranes. Nanoporous membranes are used in water treatment as an alternative to conventional methods such as flocculation or sand filtration for removing natural organic substances (Walz et al. 2014).

2.3. Photocatalysis

Photocatalytic oxidation is a method for removing micropollutants and microbial pathogens in wastewater. Photocatalysis improves degradation for those substances which are poorly degradable. One barrier to its widespread use is the slow reaction due to the limited light flux (cloudiness of the water). Current research is focusing on increasing the effectiveness of the process. In the course of this, technical challenges have to be overcome such as the optimization of the efficiency and selectivity, as well as the recovery and immobilization of the nanoscale TiO_2.

TiO_2 is one of the most frequently used photocatalysts in water/wastewater treatment. The aim of using it is to increase the efficiency by changing the particle size and the form as well as by precious metal doping and surface treatment. Additional nanomaterials such as tungsten trioxide and fullerene derivatives are being examined with respect to their possible use for photocatalytic water treatment (Qu 2013a).

3. Environmental and health aspects

3.1. Potential environmental benefits

At present, it is difficult to carry out detailed life cycle assessments since promising nanotechnological applications are frequently still not at the research and development stage. Therefore, there are currently no definitive studies available, which allow statements to be made regarding the potential for reducing environmental impacts of wastewater treatment measures using nanotechnologies. In order to establish the impacts of a product on the environment, the entire life cycle (from manufacture of raw material up to disposal) would have to be considered. This consideration takes account of the effects of reducing environmental impacts as well as the risks. The consumption of resources and energy during the manufacture of these products is generally omitted when specifying the environmental benefits (Becker et al. 2009; Gazsó and Haslinger 2014). Essential aspects for the environmental compatibility of nanomaterials are the use of raw materials, the energy consumption as well as the emissions during manufacture, use (Möller et al. 2014) and during the end-of-life phase. For many products no comprehensive data is available to assess the environmental impacts over the life cycle of the product (Greßler and Nentwich 2011). Möller et al. (2014) show in their study of the impacts of selected nanotechnological products that “innovations in the area of nanotechnology can, in principle, result in significant savings in the area of consumption of raw materials and energy”. A great deal of energy, water and environmentally problematic chemicals are often required to manufacture particular nanomaterials. The necessity of these life cycle analyses is underlined by various authors (von Gleich et al. 2007; SRU 2011; Kuhlbusch and Nickel 2011; Martens et al. 2010; Möller et al. 2012 and 2014; Mitrano et al. 2015)

3.2. Potential impacts on the environment and health

It is hoped that nanotechnological applications for treating (polluted) wastewater can contribute to a clean and healthy environment. In addition to the benefits of using nanomaterials for water treatment, it should also be borne in mind that new nanomaterials will be released into the environment and may cause unintended harmful effects on the environment and human health.

It is therefore possible that nanomaterials could enter the water cycle, in case they are not sufficiently fixed (including in the event of a malfunction) or are not adequately removed from water. No studies have been published yet regarding the release of nanomaterials from the membranes, etc. used for water treatment. In the frame of drinking water treatment, nano TiO_2 slurries are added for disinfection purposes, but the method for removing these is not clearly known (US-EPA 2010). The use of TiO_2 slurries for disinfecting drinking water has not been approved in Germany in pursuance of the *Trinkwasserverordnung* [Drinking Water Ordinance]. Investigating the potential environmental risks of nanomaterials used for wastewater treatment requires a good understanding, amongst other things, of their mobility, persistence, bioavailability, bioaccumulation capacity and ecotoxicity. At present, it is difficult to find any valid statements regarding the mobility and availability in water and sediment, and regarding the accumulation in organisms living therein. The existing test methods for studying these essential aspects within the framework of an environmental risk assessment are inadequately designed for nanomaterials and need to be specifically adapted (Hunt et al. 2013; Praetorius et al. 2014; Kühnel and Nickel, 2014).

The variety of nanomaterials used in water treatment mean that it is not possible, at the present time, to make any general statements about the possible threat to environmental organisms. Some of the nanomaterials, however, have the potential for an ecotoxic effect, so it is necessary to carry out a precise examination of applications which are open to the environment, such as those presented in this data sheet, with regard to their potential environmental risk.

Numerous studies have been conducted regarding the behavior and effect of nanomaterials in bodies of water, which have resulted in a better understanding of the processes to which nanomaterials such as TiO_2, CNT and silver nanomaterials are subjected in aqueous systems.

Nanoscale TiO_2 is one of the most studied nanomaterials in terms of its ecotoxic effect. Nano TiO_2 demonstrates an ecotoxic effect on water organisms such as algae, amphipods and fish, but usually only at relatively high exposure concentrations (Menard et al. 2011). Sublethal damage to the liver and gills and behavioral changes (swimming and breathing) are described for fish following exposure to nanoscale TiO_2 (Federici et al. 2007; Hao et al. 2009). More pronounced toxic effects were observed on aquatic microbial communities (Battin et al. 2009). TiO_2, in particular nano TiO_2 having a crystal structure of anatase, is photocatalytically active. As a result, the acutely toxic effects are clearly amplified under UV irradiation. This has been demonstrated e.g. for phytoplankton, amphipods and fish (Miller et al. 2012; Ma et al. 2012a; Wyrwoll et al. 2014). There are initial indications that nanoscale TiO_2 could be passed on via the food chain, following studies using the example of zooplankton and fish (Zhu et al. 2010). It has also been shown that nano TiO_2 can have negative effects on the reproduction and health of subsequent generations of amphipods in cases of extended duration of exposure (Jacobasch et al. 2014).

So far, adverse effects of CNT on aquatic organisms have been described in laboratory tests for various organisms including microorganisms, algae, plants, amphipods and fish (e.g. Jackson et al. 2013). The studies suggest that invertebrates react in a more sensitive way to exposure to CNT than vertebrates. The extent of the toxic effect of CNT depends on the structure, geometry, surface functionalization and any existing contaminants. Mechanical effects such as the adsorption by CNT of smaller water organisms (algae, zooplankton) can result in clumping and agglomeration thereof and trigger shading effects or causing these organisms to sink in the water column. This indirectly hinders the growth of these organisms (Long et al. 2012; Schwab et al. 2011; Zhu et al. 2009). In addition to such indirect effects, direct mechanisms of the toxic effect are also discussed. This includes the formation of oxygen radicals, which can lead to the damage of molecules such as cell membranes, DNA (deoxyribonucleic acid) and proteins and, finally, death of the cell (Jackson et al. 2013).

The general mechanism of toxic and ecotoxic effect of silver has, in general, been well studied and is based on the release of ions from the silver species when metallic silver oxidizes in contact with water (Ratte 1999). Silver (both colloidal and ionic) is classified as a severe hazard to waters (water hazard class WGK 3) due to its damaging effect with respect to water organisms.

Nanoscale silver also has a toxic effect on aquatic organisms such as microorganisms, algae, plankton and fish (e.g. summarized in Bondarenko et al. 2013). The release of silver ions – and, thus, the timely expression of the acutely and chronically toxic effect – are influenced by the size, but also the stability of the nanoscale silver. The stability is, in turn, dependent on the form and the surface quality of the particle, but also on the surrounding medium (Tejamaya et al. 2012; Gondikas et al. 2012; Kennedy et al. 2012; Ma et al. 2012b) and the quality and stability of a matrix, in case it isincorporated in a matrix. If nanoscale silver is able to penetrate biological membranes, ions can be directly released in the cell over a longer period of time (Carlson et al. 2008, Wei et al. 2010). Additional effects due to the particulate nature are discussed in the literature (Bilberg et al. 2012; Griffitt et al. 2011; Pham et al. 2012).

Inorganic nanomaterials such as CNT or TiO_2 are considered to be poorly or not degradable (demonstrated for CNT, inter alia, by Flores-Cervantes et al. 2014). Therefore, it must be assumed that they will remain in the environment for a long time. Some studies have shown that enzymatic degradation of CNT can take place under oxidative conditions. Non-functionalized CNT are therefore more difficult to degrade than CNT which have been subjected to surface functionalization (Allen et al. 2008 and 2009, Zhao et al. 2011).

The strong sorption properties of some of the nanomaterials that might be used during wastewater treatment mean that, if they were to be unintentionally released, they might also adsorb pollutants which are already present in the aquatic environment and thus change the latter's mobility and bioavailability (Farre et al. 2009; Sun et al, 2007; Tan et al. 2012). A reduction in the availability of nutrients due to their adsorption by nanomaterials is also conceivable (Jackson et al. 2013), which could trigger a deficiency state in the organisms.

Since nanomaterials have a tendency to agglomerate and therefore sediment under certain environmental conditions, it is necessary to investigate the behavior and effect of the nanomaterials used in wastewater treatment in the compartment sediment. Only a few meaningful studies have been published regarding this. The exposure to nanoscale TiO_2 did not lead to any harmful effects in larvae of chironomids and the sediment-dwelling blackworm, whilst nanosilver had significant toxic effects on these organisms (Hund-Rinke and Klawonn 2013; Khan et al. 2015; Schäfers and Weil, 2013).

With regard to human health, exposure via the dermal and oral paths is to be considered if, following wastewater treatment using nanomaterials, these remain behind in the treated water and the latter is fed into the municipal water supply. According to the level of knowledge up to now, it is to be assumed that only a very small percentage of the supplied dose of a nanomaterial can cross the intestinal barrier. However, it is not clear to what extent inflammatory bowel disease can alter the ingestion rate. It is also not clear whether the evidence which has been available to date about individual nanomaterials can be transferred to the variety of nanomaterials. It has to be assumed that size, morphology, agglomeration and the solubility of the respective nanomaterials are relevant to their ingestion and toxicity.

Surface water is used to a small extent as raw water for drinking water. At present, initial modelled concentrations of nanomaterials for surface waters exist in the ng/L and lower µg/L range (Sun et al., 2014). It needs to be checked whether the measures for drinking water production from surface water can effectively retain nanomaterials. By far the greater part of drinking water is extracted from groundwater, bank filtrate or enriched groundwater. To date, the mechanisms relevant for translocation of different nanomaterials into these compartments have not yet been conclusively clarified. However, based on the state of knowledge, the emission of nanomaterials into raw water can be estimated as rather unlikely.

4. Legal framework conditions

Within the framework of the European chemicals regulation REACH, nanomaterials are in principle recorded, but there are no specific requirements to date, which take account of the special characteristics of nanomaterials in terms of the data base and risk assessment (Schwirn et al. 2014). At the present time, various adjustment options are being discussed at European level. The higher federal authorities (Federal Institute for Occupational Safety and Health (BAuA), Federal Institute for Risk Assessment (BfR) and the German Environment Agency (UBA)) have developed a joint concept regarding this and introduced it into the discussions (UBA et al. 2013).

The European Water Framework Directive (WFD), which specifies a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater, refers to REACH and other substance regulations for the assessment of priority and river basin-related pollutants. Substances – including those dissolved out of nanomaterials – are relevant for a regulation under the WFD, if their concentrations in the water body exceed impact values (PNEC[8]). In such cases, a more detailed examination is carried out, which can result in the specification of an environmental quality standard in pursuance of the WFD, Annex V, 1.4.6.

The wastewater ordinance, the groundwater ordinance and the drinking water ordinance do not currently contain any regulations regarding nanomaterials. To adapt the regulations to nanomaterials it is necessary to demonstrate the presence of nanomaterials, qualitatively and

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[8] predicted no effect concentration

quantitatively, in order to be able to monitor compliance with a threshold which may possibly be introduced. However, no routine methods currently exist for the analytical detection of nanomaterials in complex samples.

5. Need for research and development

It is necessary to carry out more varied research and development with regard to the safe and sustainable use of nanomaterials for water treatment. The priority tasks include:

- Reliable physicochemical characterization of the nanomaterials used,
- Monitoring the release of nanomaterials during the application of various wastewater treatment technologies; development of uniform, practical and quality-assured analytical methods for this purpose,
- Development and/or adaptation of standardized test methods for adequate, quality-assured investigation of behavior and effect of nanomaterials on the environment and on humans,
- Conducting life cycle analyses for the use of nanotechnology during wastewater treatment (under realistic conditions) and comparison with conventional techniques,
- Transfer of suitable technologies into practice.

6. Conclusion

Treating wastewater with nanomaterials may possibly contribute to a better quality of the water from wastewater treatment plants. However, most applications are still in development. In addition to the benefits of using nanomaterials for treating water and wastewater, it should be taken into account that nanomaterials could have unintended impacts on the environment and human health. Numerous studies are currently being conducted into both their behavior and their effect on the environment and on humans, as well as a possible accumulation in the environment and in the organism, none of which can be conclusively assessed to date. Ahead of using nanomaterials for treating wastewater, it must also be ensured that the nanomaterials are integrated as firmly as possible into the respective matrices, thus ensuring that they cannot enter the treated wastewater and, therefore, bodies of waters. The use of nanomaterials must be weighed up, taking account of the ecological consequences for the environment. The technical further development should always be accompanied by a risk assessment and drafting of a life cycle assessment.

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Autors:
This fact sheet was compiled by the „Nanotechnology“ working team of the German Environment Agency. In particular, the following persons have contributed:

Christine Winde (III 2.5 – Monitoring Methods, Waste Water Management)
Dr. Wolfgang Dubbert (III 2.1 – General Aspects, Chemical Industry, Combustion Plants)
Dr. Kathrin Schwirn (IV 2.2 – Pharmaceuticals, Washing and Cleaning Aspects, Nanomaterials)
Dr. Doris Völker (IV 2.2 – Pharmaceuticals, Washing and Cleaning Aspects, Nanomaterials)
Petra Apel (II 1.2 – Toxicology, Health-related Environmental Monitoring)

Further legwork by

Dr. Sondra Klitzke (II 3.3 – Drinking-water Resources and Treatment)
Christian Liesegang (III 2.1 – General Aspects, Chemical Industry, Combustion Plants)