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Risk of Nanowastes

Niebezpieczeństwo nanoodpadów

Recent nanotechnology proves to be a field of growing scientific interest as the properties of engineered nanomaterials (ENMs) can be utilized in a broad spectrum of applications. It should be noted that the nanmaterials can be released to the environment at any stage of the life cycle of products. The term nanowaste refers to waste that contains materials with nanoscale dimensions. The objectives of this paper are review of literature data in the field of nanowaste management and presentation the uncontrolled releases of nanomaterials into the environment through nanowaste streams and to identify possible directions of action in the field of nanocontaminants deactivation.

Keywords: **nanotechnology, nanoparticles, nanomaterials, nanowastes management**

Introduction

Resent nanotechnology proves to be a field of growing scientific interest as the properties of engineered nanomaterials (ENMs) can be utilized in a broad spectrum of applications. In 2008, the International Organization for Standardization (ISO) classified nanomaterials into three main groups: nanoparticles (all three dimensions between 1 and 100 nm); nanoplates (one dimension between 1 and 100 nm); and nanofibers (two dimensions between 1 and 100 nm). The global ENMs production of 2010 was estimated as 268,000 to 318,000 metric tons and it has been increasing at a rate of 25% per year. Between 2006 and 2011, the number of products containing nanomaterials has been multiplied by 5 at the global level, and more than 1,300 products have been identified to contain them [1-4]. Part et al. [4] stated that more than 1,600 consumer products are listed in a database to be containing ENMs. The global market of ENMs was estimated on the level 2 trillion EUR in 2015 [1, 2]. Manufactures ENMs comprise seven main classes: carbonaceous nanomaterials (e.g., carbon nanotubes); semiconductors (e.g., quantum dots); metal oxides (e.g., zinc oxide); nanopolymers (e.g., dendrimers); nanoclays; emulsions (e.g., acrylic latex); and metals (e.g., silver). Except for carbon black, the TiO_2 nanomaterial is produced most often; in order of most to least produced ENMs, TiO_2>SiO_2>ZnO>Fe and FeOx>Al_2O_3>CeO_2>CNT>Ag [1, 5, 6]. It should be noted that the nanomaterials can be released to the environment at any stage of the life cycle of products (LCA - Life Cycle Assessment), from the manufacture, use, and disposal or recycling processes. The ENMs may exist in single, aggregated, or agglomerated forms and have various shapes, coatings, and surface functionality. In the environment ENMs can undergo a number of potential transformations that depend on the properties both of the nanomaterials and of the receiving medium. It is hold for creating recent means of detecting pollutants - hazardous nanomaterials - which are called „nanocontaminants" [6-8]. The effects of many ENMs on human health and environment are not yet well understood. Not all NMs possess hazardous properties. In fact, studies performed on the same type of nanomaterials are in disagreement, some studies show their biocompatibility, while others prove their potentially hazardous nature [9-12]. The potential risk of these materials also depend on their solubility, size, shape and agglomeration among other physicochemical parameters [13]. The smaller a particle, the greater it's surface area to volume ratio and the higher its chemical reactivity and biological activity. Because of their large surface area, nanoparticles will, on exposure to tissue and fluids, immediately adsorb onto their surface some of the macromolecules they encounter. This may, for instance, affect the regulatory mechanisms of enzymes and other proteins [8, 9, 11, 14, 15].

Despite the observed trend of ENMs using and the associated risk, waste containing nanomaterials are currently disposed along with conventional waste without any special precautions or treatment. This raises the question as to whether existing waste treatment processes are able to effectiviely minimise the risk that may be linked to ENMs.

This paper is a review of the recent literature information and data in the field of nanowaste management. The objectives of this paper are to highlight problems related to uncontrolled release of ENMs into the environment through nanowaste streams and to identify possible directions of action in the field of nanocontaminants deactivation.

1. Nanowaste

The term nanowaste refers to waste that contains materials with nanoscale dimensions. Nanowaste management is a new challenge, which focuses attention of many researchers. A simplified pathway from nanotechnology to nanowaste is presented in Figure 1. Development and applications of nanotechnology emphasize the need for continuous monitoring of the fate of nanoproducts. The researchers suggest, that the best way to reduce the amount of nanowaste is recycling [4, 8]. Also, there is a need to develop research in the scope of nanowaste treatment and to reduce the unintentional release into the environment. But the lack of adequate tools and methods to measure emissions of nanoparticles accurately and significant gaps in data, monitoring, and technology hinder the precise determination of nanoparticle emissions [5]. From the other hand, governments have to take a proactive approach towards developing a waste strategy for nanomaterials, for prevention against long-term unintended consequences.

The possible sources of ENMs entering waste treatment facilities are fairly well identified among the four typical treatment processes:
– recycling: municipal solid waste, end of life products;
– incineration: municipal solid waste, sludge and biosolids from wastewater treatment plants;
– landfilling: municipal solid waste, fly ash and bottom ash from incinerators, sludge and biosolids from wastewater treatment plants;
– wastewater treatment: household drainage, commercial and industrial wastewater, landfill leachate [2].

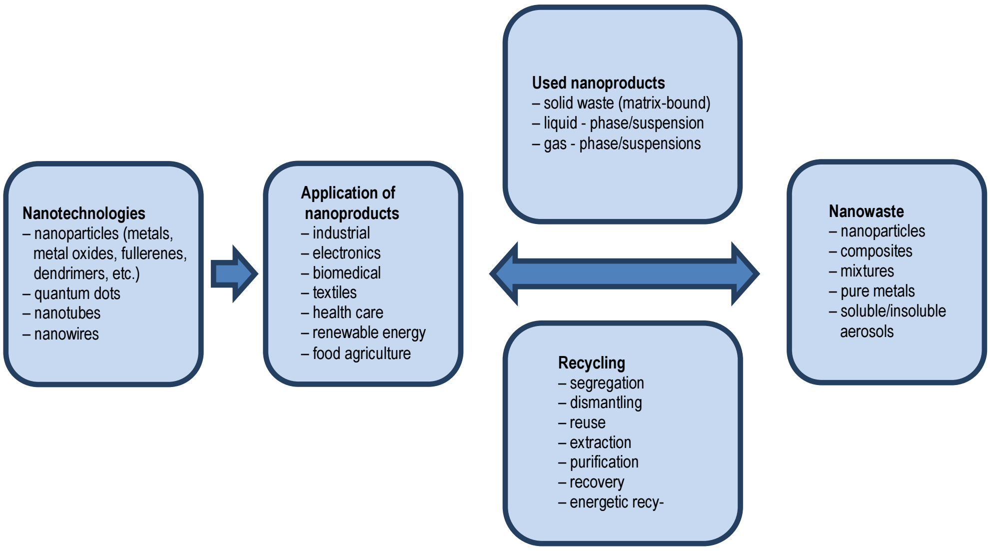

Fig. 1. Towards "green nanoscience": a schematic showing pathway from nanotechnology to nanowaste [8]

2. Ecological and health impacts

The large surface area, large quantum effects, biological reactivity, shape and size, deformability, durability, tendency to aggregate, optical sensitivity, and hydrophobicity among other surface characteristics of ENMs may aid faster bonding with pollutants (e.g. cadmium and organics). Consequently, this may facilitate faster translocation of these pollutants through air, soil and water. NMs are known to move with high velocities through aquifers and soils, and may act as suitable carriers for rapid and long-range transportation of hazardous chemicals dispersing them widely throughout the environment. For example, organic compounds such as polycyclic aromatic hydrocarbons (PAHs) can be adsorbed by carbon nanotubes causing an enhancement of the PAH toxicity, and in addition, ENMs have been shown to exert affects on the fate, transformation, and transportation of chemical compounds in the environment [16, 17].

A number of recently published review papers in the field of eco-toxicology conclude that ENMs carry the risk of eco-toxic impacts. Observation made by in vitro as well as in-vivo studies support the hypothesis that the bioavailability of ENPs is very specific to the type of nanomaterials as well as to transformations they undergo in the environment [14, 18]. Moreover, environmental conditions, including exposure to other pollutants, determine how tolerant organisms are against ENMs [9, 18, 19]. The toxic impacts of same ENMs on natural organisms, as diverse as protozoa, bacteria, fungi, crustaceans, amphibians, plants, and mammals including humans are stated. The modes and degree of toxic impacts is varied and strongly depends on the concreto ENM exposure and target organism under study. In addition, the specific environmental conditions play an important role as well as the functionalisation of ENMs [10, 12, 19-21]. The studies of Buzea et al. [9] indicate that carbon nanotubes (CNTs) are extremely toxic on human, producing more damage to the lungs than carbon black or silica. Varieties of CNT aggregates, and some carbon blacks, were shown to be as cytotoxic as asbestos. Silver nanoparticle aggregates were found to be more toxic than asbestos, while titanium oxide, alumina, iron oxide, zirconium oxide were found to be less toxic. It was stated that bioaccumulation and bio-magnification of ENMs can occur along trophic chains. This may increase the risk of human exposure through the consumption of contaminated food such as fishery products [22]. The examples of the selected ENPs, their applications, risk characterization and goals of the current study are presented in Table 1.

Musee [16, 23] present classification of nanowastes due to their toxic effects in humans and other ecological systems:

- ***Class I nanowastes***: hazard - very low or no toxic effects; exposure - low to high; risk profile - none to very low.

  Examples of such products, which later form the class of nanowaste are: display backplanes of television screens, solar panels, memory chips, polishing agents. For the type of nanowaste are not special disposal requirements. Hazard during the waste management may be caused by toxicity of the bulk parent materials to humans and the environment in case of exceeding the concentration limit.

- ***Class II nanowastes***: hazard - harmful or toxic effects; exposure - low to medium; risk profile - low to medium.

  This group includes used products such as: display backplanes, solar panels, memory chips, polishing agents, paints and coatings. Nanowaste of *Class II* due to toxicity can cause acute or chronic effects, so it is recommended that appropriate and optimum waste management during handling, transportation or disposal processes.

- ***Class III nanowastes***: hazard - toxic to very toxic effects; exposure - low to medium; risk profile - medium to high.

Examples of used products are: food packing, food additives, wastewater containing personal care products, polishing agents, pesticides. For the class of nanowaste proper protocols for managing of hazardous waste streams in the entire waste management chain are recommended. Furthermore, for the nanowaste is need to determine if current waste management infrastructure is adequate to safely dispose of the hazardous waste.

- ***Class IV nanowastes***: hazard - toxic to very toxic effects; exposure - medium to high; risk profile - high.

  Examples of nanowaste classified in this group are: paints and coatings, personal care products, pesticides. Due to the toxic properties of these nanowaste their streams should be disposed in specialized hazardous wastes designated sites. The mismanagement of nanowaste classified into *Class IV* can result in a significant threat to humans and the environment.

- ***Class V nanowastes***: hazard - very toxic to extremely toxic effects; exposure - medium to high; risk profile - high to very high.

  This group includes used products such as: pesticides, sunscreen lotions and food and beverages containing fullerenes in colloidal suspensions. Such nanowaste should be dispose only in specialized hazardous waste streams designated sites. Inadequate waste management can lead to significant pollution of various ecological system. For this group of nanowaste immobilization and neutralization are recommended as the most effective treatment techniques.

3. Recycling of waste containing nanomaterials

Nanomaterials that are hazardous, toxic or chemically reactive should be neutralized. Where possible, nanowaste should be recycled. But often, products containing ENMs are being recycled along with their analogous products without nano materials. No separation or separate collection of product containing ENMs solely due to their nanomaterial-content is known. Also, the existing recycling techniques do not take into account the possible nanospecific risks coming from waste containing ENMs. Information about the fate of nanomaterials in recycling processes is only beginning to emerge. Mostly, exposure scenarios are based on modelling, and not on evidence. It is extremely difficult to quantify and monitor the long-term release of ENM during the final disposal of ENM containing products [24]. Therefore it is important to understand the properties of specific nanowastes before developing effective disposal practices. The developed safety measures and disposal procedures necessary for handling nanowaste must be based on current knowledge and take into account existing legislation. The disposal procedures must ensure that the waste is deactivate of its hazardous properties. Depending on the type of the material, thermal, chemical or physical processing of nanotechnology-containing waste are possible deactivation solution [13].

Table 1. **Examples of the selected ENPs, their applications, risk characterization and goals of the study [4, 8, 16, 23]**

Nanoparticles	Example of applications	Hazard	Exposure potency	Risk and disposal	Goals of the study
Ag	Textile, sport equipment, antimicrobial agent in domestic applications, personal care products, food packing, paints	Medium	High	Medium	Influence of ENMs on emission of particulate matter; Fate during incineration and effect on emissions of particulate matter; Effects of ENMs on aerobic and anaerobic biochemical processes in landfill leachates
TiO_2	Personal care products, beverages, solar panels, paints, coating, food packing, batteries, agrichemicals, polishing agents	Low	High	Low	Influence of ENMs on emission of particulate matter; Fate during incineration and effect on emissions of particulate matter; Effects of ENMs on aerobic and anaerobic biochemical processes in landfill leachates
ZnO	Beverages, agrichemicals, polishing agents, paints, sunscreen, batteries	Medium	High	Medium	Effects of ENMs on aerobic and anaerobic biochemical processes in landfill leachates
$SWCNT_s$	Sport equipment, memory chip, automobile parts	High	Medium	Low to medium	Colloidal stability, leachability, and mobility of $SWCNT_s$ in landfill leachate while changing ionic strength, humic acid content and pH
CdSe	Solar panels, memory chip, paints, coatings	High	Medium to high	Medium	Influence of ENMs on emission of particulate matter; Fate during incineration and effect on emissions of particulate matter
Fe_2O_3	Concentrate additive, pesticides, personal care products	Medium	High	Medium	Fate during incineration and effect on emissions of particulate matter

Abbreviation: $SWCNT_s$ - singled-walled carbon nanotubes

4. Knowledge gaps of nanowaste disposal

Knowledge gaps may limit the effective applications of existing regulatory management controls. Key gaps include a lack of ENMs characterization and quantitative data on toxicity. The scientific knowledge of ENMs, their fate is progressing and needs to be understood further to guide effective waste management approaches for varied waste streams containing nanomaterials. But, recent research in the area raises complex issues to consider. This is evidence that same ENMs are released in landfill from product containing nanomaterials and from other nanowaste sources (for example domestic and industrial wastewater). The main areas of further research inter alia are: development of analytical chemistry test methods to identify ENMs in environmental media, characterization and quantification of the issue and understanding of the chemical and environmental processes, understanding the effective and constraints of current methods and technologies of removal ENMs from waste [2, 10]. The Federal Office for the Environment (FEON) appointed the Working Group "Disposal of Nanowaste", which identified substantial knowledge gaps on the type and quantities of nanowaste, and on the behaviour of nanomaterials in waste treatment installations. The Working Group suggests using the prepared conceptual study to perform a practical test with the participation, on the one hand, of the producers, and also of industrial and commercial processors, of nanomaterials, and, on the other hand, companies in the disposal business (disposers of special waste, special waste incineration plants, etc.). The disposal of nanowaste must be performed in an environmentally sound manner and include:

Pretreatment of nanowastes inside of industrial factories

Industrial factories which produce or process nanomaterials should take steps to reduce the amount of waste and for neutralize their dangerous effects. As far as technical and technological possibilities the generated nanowaste should be processed in the same companies. The nanowaste treatment should be carried out with the use of the best available methods and equipment in order to deprive of their toxic properties (e.g. dissolution of metallic nanomaterials in suitable acid baths, or sintering at high temperatures).

Waste management

Industrial factories which produce or process nanomaterials with free or releasable particles or rods should implemented procedures with high standards for safe working and waste management. The procedures in the factories in respect of waste management must guarantee safety, health and environmental protection. Moreover, the procedures must be recorded, and they should include collection, documented, packing and passing on for waste disposal. The potential sources of nanowaste with free of releasable nanoparticles must be identified and the appropriate handling stipulated in the factory documentation.

Reduction of exposure of workers and of emissions to the environment

Because of the potential for worker exposure during the production processes and nanowaste disposal, the release of NMs (in dust or aerosol form) and emissions to the environment should be kept as low as possible. The exposure to NMs with substantial hazard potential or unknown effects should be determined on the base of the nanoparticles concentration in the ambient air while taking into account the duration of the effect. Limiting exposure is possible by restricting use of NMs in the form of dust and aerosol and by shortening the time of their application. The nanowaste should not be collected and passed on in powder form, but as dispersions, pastes, granulates, etc. Such actions will allow to limit the hazard potential in a large extent during subsequent handling (transport, filling of installations, disposal) [25].

Nanotechnology is growing at an exponential rate, but it is clear that issues related to the disposal and recycling of nanowaste will grow at an even faster rate if left unchecked.

Results and conclusions

To reduce the potential risk of releases of ENMs to the environment, a combination of improvement in segregation and recovery/recycling efforts, adequate landfill design and operation, effective treatment technologies and access to specialised facilities are necessary. Identification, classification and labelling will support the implementation of improved and appropriate waste management approaches and the application of appropriate technologies to manage potential risks posed by certain ENMs. Adapting and clarifying existing legislative frameworks and further waste management approaches will be need to restrict the follow of hazardous ENMs. The important direction of current and future investigation are fate of the EMNs in complex waste matrices and developing accurate methods for analyses, assessment and monitoring nanowaste in the environment.

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Streszczenie

Obecnie nanotechnologia stanowi obszar rosnącego zainteresowania naukowego ze względu na specyficzne właściwości produkowanych nanomateriałów (ENMs), znajdujących szerokie spektrum zastosowań. Należy zauważyć jednak, że nanomateriały mogą być uwalniane do otoczenia na każdym etapie cyklu życia produktu. Termin nanoodpady odnosi się do odpadów, które zawierają w swoim składzie materiały o wymiarach charakterystycznych dla nanoskali. Celem niniejszego artykułu jest przegląd danych literaturowych z zakresu gospodarki nanoodpadami, prezentacja niekontrolowanego uwalniania się nanomateriałów do środowiska ze strumienia nanoodpadów oraz określenie możliwych do realizacji kierunków działania w zakresie dezaktywacji nanozanieczyszczeń.

Słowa kluczowe: **nanotechnologia, nanocząstki, nanomateriały, gospodarka nanoodpadami**