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Semi-quantitative analysis of solid waste flows from nano-enabled consumer products in Europe, Denmark and the United Kingdom – Abundance, distribution and management

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ABSTRACT

Many nano-enabled consumer products are known to be in the global market. At the same, little is known about the quantity, type, location etc. of the engineered nanomaterials (ENMs) inside the products. This limits the scientific investigations of potential environmental effects of these materials, and especially the knowledge of ENM behaviour and potential effects at the end-of-life stage of the products is scarce. To gain a better understanding of the end-of-life waste treatment of nano-enabled consumer product, we provide an overview of the ENMs flowing into and throughout waste systems in Europe, Denmark and the United Kingdom. Using a nanoproduct inventory (nanodb.dk), we performed a four-step analysis to estimate the most abundant ENMs and in which waste fractions they are present. We found that in terms of number of products: (i) nano silver is the most used ENM in consumer products, and (ii) plastic from used product containers is the largest waste fraction also comprising a large variety of ENMs, though possibly in very small masses. Also, we showed that the local waste management system can influence the distribution of ENMs. It is recommended that future research focus on recycling and landfilling of nano-enabled products since these compartments represent hot spots for end-of-life nanoproducts.

1. Introduction

The global market for nano-enabled consumer products is expanding steadily (Hansen et al., 2016). Consequently, increasing amounts of consumer waste containing engineered nanomaterials (ENMs) are being generated which will eventually find their way into various forms of waste treatment processes (incineration, waste water treatment plants, etc.) not originally designed to treat such materials (OECD, 2016). As previously discussed in the literature (e.g. Nowack et al., 2012; Part et al., 2015) the emergence of nanoproducts raises a number of important issues when it comes to these products' end-of-life (EOL), waste treatment and waste handling, as very little is known about: (i) the potential transformations of nanoproducts and nanomaterials during different waste treatments, (ii) the interactions between ENMs and other constituents of waste, (iii) the magnitude of ENMs released into the environment after waste treatment and (iv) the potential transformations/effects of modified ENMs in the environment.

Some experimental studies have investigated the fate and behaviour of nanomaterials in simulated landfill conditions (e.g. Bolyard et al., 2013) and their results indicate that organic matter influences the stability and mobility of ENMs. However, these studies look at the behaviour of pristine ENMs which are usually not expected to enter the environment (Nowack et al., 2012). Another way to approach these concerns is to gain a basic understanding of ENMs flowing into and throughout waste systems, addressing, for instance, which types of nanoproducts are expected to enter current waste management systems, as well as which kinds are potentially the most abundant and in what form they reach waste treatment facilities.

Different modelling approaches have been used to address some of the abovementioned aspects, including material flow modelling (Gottschalk et al., 2009; Walser and Gottschalk, 2014; Sun et al., 2014), market analysis (Keller and Lazareva, 2014; Keller et al., 2014; Boldrin et al., 2014), life cycle assessment (Pourzahedi and Eckelman, 2015; Hischier et al., 2015) and modelling by categorisation, based on consumer product inventories (Asmatulu et al., 2012).

Probabilistic material flow models have been used to predict concentrations of ENMs in the environment (Gottschalk et al.,

Abbreviations: ENMs, engineered nanomaterials; ENM, engineered nanomaterial.

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2009; Walser and Gottschalk, 2014; Sun et al., 2014) and in recycling processes (Caballero-Guzman et al., 2015). These studies use probabilistic distribution curves as input data instead of the generally uncertain and inadequate datasets available on ENM fate and behaviour in the environment.

Recently, Sun et al. (2014) modelled the concentrations of selected ENMs (nano-TiO_2, nano-Ag, nano-ZnO, fullerenes and CNTs) in environmental and technical compartments and compared these with non-nano metal-based counterparts (TiO_2, Ag, ZnO). Technical compartments refer to sewage treatment plants, waste incineration plants, landfills and recycling stations as well as the "emissions" related to these, such as sewage sludge and bottom ash. Compared to the environmental compartments (air, soil, sediment and water), the highest modelled concentrations were estimated for the technical compartments. Among these, the highest concentrations are expected to occur in sewage sludge, followed by solid waste and waste incineration ashes (fly and bottom ash). The technical compartments presented concentrations in the mg/kg range, whereas the environmental compartments only showed them in the ng-μg/kg range, though it should be mentioned that these values represent modelled yearly increases in each compartment. These findings support the relevance of further studies on ENM quantification and characterisation in waste treatment compartments since they constitute a likely sink for ENMs.

The modelling approaches have a mayor limitation namely that the analytical techniques currently available are not able to detect ENMs in complex matrices. This means that the models cannot be validated with actual measurement of ENMs released into the environment or during waste treatment (Part et al., 2015; Nowack et al., 2012). The challenges of detecting ENMs in waste streams have recently been reviewed by Part et al. (2015). In this review, promising techniques for nanomaterial quantification, such as separation techniques combined with spectrometry-based methods and imaging, are discussed. However, the authors also highlight the fact that currently these analytical techniques are not able to distinguish between engineered and naturally occurring nanomaterials.

In general, the abundance of nanoproducts, the type of nanoproducts, the nanomaterial used, the form of the nanomaterial and the product matrix, as well as waste handling and treatment processes, will have a profound impact on the EOL of the ENMs.

The aim of this paper is to provide a systematic and consistent basis for prioritising efforts related to handling ENMs within the waste management system. This is achieved by: (i) developing tools for the analysis of nanoproducts in solid waste flows, (ii) assessing the relative importance of ENMs and waste types, (iii) identifying critical aspects with respect to specific ENMs and waste treatment combinations and (iv) establishing waste scenarios (for the EU, Denmark and the UK) to identify the waste treatment options involved in this regard.

2. Methodology

The method for conducting the analysis of waste flows is divided into four steps:

1. Categorisation of available nano-enabled products into waste material fractions
2. Estimation of the types of ENMs present in waste material fractions
3. Estimation of the region-specific waste management of individual waste material fractions
4. Combination of steps 2 and 3, to determine the distribution of ENMs routed to specific waste treatment options.

The four steps are explained in detail in the following sections.

2.1. Step 1: Categorisation of products available on The Nanodatabase

The first step in the process towards mapping the abundance, distribution and waste treatment of nanoproducts is to assign individual nanoproducts to waste material fractions. To do this, we used The Nanodatabase (nanodb.dk), an online inventory of products known to be available to European consumers either via retailers or via online shops. The database was established by DTU and others in 2012 and currently contains 2312 products (8/4-2016, nanodb.dk). Information about each product is collected based on data that producers provide publicly online, such as the type of ENM or a description of the product. A more thorough description of how products are included in the database is given in the recent paper by Hansen et al. (2016).

Based on the information available on The Nanodatabase, we identified the main matrix material of each individual product and its corresponding waste material fraction, e.g. a product in a plastic container falls into the waste fraction named "Plastic packaging". Categorisation is based on an image of the product, along with any other information made available by the manufacturer online. In some cases, we created specific fractions which were adapted to products on the database, e.g. "Plastic, other." These products made from plastic, e.g. hockey sticks, food containers or baby bottles, are separated from plastic packaging waste, since the ENMs in these plastic products, contrary to the case of plastic packaging, are usually embedded in the plastic or are coated on the surface, and they are considered potentially more suitable for recycling. Hence, they might also be handled differently in the waste management system. On occasion it was not possible to create a homogenous fraction, for example when a product consisted of more than one main material which could not readily be separated (e.g. camera lenses, a baby carriage and a water filtering unit). These products were grouped into a "Multi-material waste" fraction, comprising products of many sizes and applications. Other products in The Nanodatabase in reality consist of multiple individual products, e.g. an automotive cleaning kit including products in both plastic and metal containers, and in these cases we adjusted the data before analysis, so each individual product in the kit was allocated to its own waste material fraction. This means that these products were copied and routed to several waste fractions, and therefore the number of products in our analysis varies slightly from what can be found in The Nanodatabase. Products were categorised as unknown if no image was available showing the specific product and the container it was sold in, or it couldn't be derived from the product description.

2.2. Step 2: Identification of the types of ENM present in the waste material fractions

For each product in The Nanodatabase, the identity of ENMs claimed to be used in the product was noted, if reported by the manufacturer. In total the ENM was reported for 970 products (8/4-2016, nanodb.dk). This information was used subsequently to identify ENM types in the waste material fractions, which in turn allowed for an assessment of the relative importance of the ENM types in each waste fraction. It has to be noted that for 40% of the products in the database, the identity of the ENM is not described by the manufacturer or others, and these products were therefore not included in our analysis of waste flows.

2.3. Step 3: Identification of region-specific waste management of individual waste material fractions

From Eurostat (http://ec.europa.eu/eurostat/web/waste), we collected the most recent data on the waste treatment of selected waste fractions and included four possible waste management