ARTICLE IN PRESS

Waste Management xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

A review of the fate of engineered nanomaterials in municipal solid waste streams

Florian Part [a], Nicole Berge [b,*], Paweł Baran [c], Anne Stringfellow [d], Wenjie Sun [e], Shannon Bartelt-Hunt [f], Denise Mitrano [g], Liang Li [b], Pierre Hennebert [h], Peter Quicker [c], Stephanie C. Bolyard [i], Marion Huber-Humer [a]

[a] Department of Water-Atmosphere-Environment, Institute of Waste Management, University of Natural Resources and Life Sciences, Muthgasse 107, 1190 Vienna, Austria
[b] Department of Civil and Environmental Engineering, University of South Carolina, 300 Main Street, Columbia, SC 29208, United States
[c] Unit of Technologies of Fuels, RWTH Aachen University, Wüllnerstraße 2, 52062 Aachen, Germany
[d] Faculty of Engineering and the Environment, University of Southampton, SO17 1BJ, Southampton, England, United Kingdom
[e] Department of Civil and Environmental Engineering, Southern Methodist University, 3101 Dyer Street, Dallas, TX 75205, United States
[f] Department of Civil Engineering, University of Nebraska-Lincoln, 1110 S. 67th St., Omaha, NE 68182-0178, United States
[g] Process Engineering, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland
[h] National Institute for Industrial and Environmental Risk Assessment (INERIS), BP 33, 13545 Aix-en-Provence Cedex 4, France
[i] Environmental Research & Education Foundation, 3301 Benson Drive, Suite 101, Raleigh, NC 27609, United States

ARTICLE INFO

Article history:
Received 20 September 2017
Revised 15 January 2018
Accepted 6 February 2018
Available online xxxx

Keywords:
Engineered nanomaterials
Waste management
Landfills
Recycling
Incineration
Biological treatment

ABSTRACT

Significant knowledge and data gaps associated with the fate of product-embedded engineered nanomaterials (ENMs) in waste management processes exist that limit our current ability to develop appropriate end-of-life management strategies. This review paper was developed as part of the activities of the IWWG ENMs in Waste Task Group. The specific objectives of this review paper are to assess the current knowledge associated with the fate of ENMs in commonly used waste management processes, including key processes and mechanisms associated with ENM fate and transport in each waste management process, and to use that information to identify the data gaps and research needs in this area. Literature associated with the fate of ENMs in wastes was reviewed and summarized. Overall, results from this literature review indicate a need for continued research in this area. No work has been conducted to quantify ENMs present in discarded materials and an understanding of ENM release from consumer products under conditions representative of those found in relevant waste management process is needed. Results also indicate that significant knowledge gaps associated with ENM behaviour exist for each waste management process investigated. There is a need for additional research investigating the fate of different types of ENMs at larger concentration ranges with different surface chemistries. Understanding how changes in treatment process operation may influence ENM fate is also needed. A series of specific research questions associated with the fate of ENMs during the management of ENM-containing wastes have been identified and used to direct future research in this area.

Contents

* Corresponding author.
E-mail address: berge@engr.sc.edu (N. Berge).

https://doi.org/10.1016/j.wasman.2018.02.012
0956-053X/

Please cite this article in press as: Part, F., et al. A review of the fate of engineered nanomaterials in municipal solid waste streams. Waste Management (2018), https://doi.org/10.1016/j.wasman.2018.02.012

1. Introduction

Escalating production and subsequent incorporation of engineered nanomaterials (ENMs) in consumer products increases the likelihood of their release to the environment. ENMs including titanium dioxide (nano-TiO_2), zinc oxide (ZnO), silver (nano-Ag), gold (nano-Au), C_{60} fullerenes, carbon nanotubes (CNTs), graphite, and silica (nano-SiO_2) have been incorporated in several commercially-available and commonly discarded products, including plastics, inkjet printer ink, textiles, cosmetics, sunscreens, cleaning materials, and sporting goods (Hansen et al., 2016; Lesyuk et al., 2015). The increased use of ENM-containing products warrants an immediate understanding of potential adverse effects ENMs may impart to the environment and human health (Mahaye et al., 2017; Mattsson and Simkó, 2017; Musee, 2017; Schaumann et al., 2014; Valsami-Jones and Lynch, 2015). As ENM-containing products reach the end of their useful life, the development of appropriate end-of-life management strategies is critical to minimize human and/or environmental exposure. Several modelling-based studies describing different aspects of discarded ENMs and their fate in the environment (e.g., Boldrin et al., 2014; Caballero-Guzman et al., 2015; Keller et al., 2013; Mueller et al., 2013; Mueller and Nowack, 2008; Sun et al., 2016, 2014; Suzuki et al., 2018; Walser and Gottschalk, 2014) highlight the important role different waste management processes may play in ensuring appropriate and adequate disposal of ENM-containing products.

Significant knowledge and data gaps associated with the fate of ENMs during waste management processes exist that limit our current ability to develop appropriate end-of-life management strategies. A fairly limited number of laboratory and field-scale studies evaluating the release and/or environmental fate of ENMs from discarded materials in conditions representative of waste management processes have been conducted (e.g., Bolyard et al., 2013; Bouillard et al., 2013; Lozano and Berge, 2012; Ounoughene et al., 2015; Walser et al., 2012). However, very little knowledge exists about the mass of ENMs discarded, the transfer of ENMs from their parent products during waste management, and the fate and transport of ENMs during incineration, composting, recycling, and landfilling processes. Understanding ENM behaviour in these processes is complicated by the lack of analytical techniques to detect ENMs in the complex solid, liquid, and gaseous matrices associated with these processes (Laborda et al., 2016; Mackevica and Foss Hansen, 2016; Part et al., 2015; Reinhart et al., 2016).

In response to this emerging management challenge, in 2014 the International Waste Working Group (IWWG) formed the Task Group on Engineered Nanomaterials in Waste. The members of this task group include experts in the areas of waste management and nanomaterial fate and transport. The purpose of this task group is to serve as a technical resource on issues associated with the end-of-life management of ENM-containing wastes. The ultimate goal of this task group is to develop guidance on the appropriate end-of-life management strategies for these materials. This review paper was developed as part of the activities of this task group. The specific objectives associated with this review paper are to assess the current knowledge associated with the fate of ENMs in commonly used waste management processes, including key processes and mechanisms associated with ENM fate and transport in each waste management process, and to use that information to identify data gaps and research needs in this area. Currently available literature associated with ENMs embedded within waste products, the potential for release of ENMs from these products, and their potential fate during waste degradation (e.g., composting), recycling, incineration, and landfilling was assessed and reviewed.

2. Review scope and methods

Generally, nanomaterials are defined as materials that have at least one external dimension or surface structure in the nanoscale (i.e. from, 1 to 100 nm). ENMs are defined as nanomaterials designed for a specific purpose or product (ISO/TS 80004-1:2015). The focus of this review paper is on understanding the current knowledge associated with the fate of ENMs in solid waste treatment processes (e.g., composting, recycling, incineration, and landfilling). Because this review focuses specifically on the fate of ENMs during waste management processes, this review does not differentiate between a product that may be specifically classified as a nanowaste according to previously published definitions of this special type of waste provided by Boldrin et al. (2014) and Musee (2011b). Musee (2011b) define nanowaste as "waste stream(s) containing ENMs, or synthetic by-products of nanoscale dimensions, generated either during production, storage and distribution, or waste stream(s) resulting from the end of a lifespan of formerly nanotechnologically enabled materials and products, or items contaminated by ENMs such as pipes, personal protection equipment, etc.", while Boldrin et al. (2014) define nanowaste as "only separately collected or collectable waste materials which are or contain ENMs. This means that nanowaste can include (1) ENMs as a single fraction, e.g. by-products from manufacturing of nanoproducts, (2) end-of-life (EOL) nanoproducts and (3) individual waste materials contaminated with ENMs, for example, sludge from wastewater treatment." In this review, the source of ENMs may be from any discarded materials (e.g., consumer products, manufacturing wastes, biosolids, contaminated products, such as personal protection equipment) and is therefore generally referred to as "ENM-containing wastes". Additionally, nanomaterials generated as an unintentional by-product of a process ("incidental