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# Exposure to airborne engineered nanoparticles in the indoor environment

Marina E. Vance [a], Linsey C. Marr [b,*]

[a] Institute for Critical Technology and Applied Science, Virginia Tech, 233 Kelly Hall, Blacksburg, VA 24061, United States
[b] Department of Civil and Environmental Engineering, Virginia Tech, 418 Durham Hall, Blacksburg, VA 24061, United States

## HIGHLIGHTS

- One-tenth of consumer products present a potential for aerosolization.
- People will be exposed to wet and/or dry aerosols from nano-enhanced products.
- Health and fitness products are most likely to lead to inhalation exposures.
- Metal and metal oxide nanoparticles are most likely to lead to inhalation exposures.
- Subacute aerosol exposure levels are expected in indoor environments.

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## ABSTRACT

This literature review assesses the current state of knowledge about inhalation exposure to airborne, engineered nanoparticles in the indoor environment. We present principal exposure scenarios in indoor environments, complemented by analysis of the published literature and of an inventory of nanotechnology-enhanced consumer products. Of all products listed in the inventory, 10.8% (194 products) present the potential for aerosolization of nanomaterials and subsequent inhalation exposure during use or misuse. Among those, silver-containing products are the most prevalent (68 products). Roughly 50% of products would release wet aerosols and 50% would potentially release dry aerosols. Approximately 14% are cleaning products that can be broadly used in public indoor environments, where building occupants may be exposed. While a variety of nanomaterial compositions have been investigated in the limited number of published release and exposure studies, we identified a need for studies investigating nanofibers (beyond carbon nanotubes), nanofilms, nanoplatelets, and other emerging nanomaterials such as ceria and their nanocomposites. Finally, we provide recommendations for future research to advance the understanding of exposure to airborne nanomaterials indoors, such as studies into indoor chemistry of nanomaterials, better nanomaterial reporting and labeling in consumer products, and safer design of nanomaterial-containing consumer products.



## 1. Introduction

Nanotechnology involves the synthesis or manipulation of materials at the scale of approximately 1–100 nm. Although materials at this scale have been used for centuries and studied for decades, as *colloids* to chemists and environmental scientists and as *ultrafine particles* to atmospheric scientists and health researchers, the terms "nanotechnology" and "nanoscience" have entered the lexicon only in the past couple of decades. The word "nano," as in nanotechnology, nanoscience, nanomaterial, and nanoparticle, implies that the entities have novel or enhanced properties when compared to their bulk counterparts. In theory, engineered nanomaterials can be distinguished from incidental and naturally-occurring nanomaterials because they are specifically produced to present particular properties.

Popular nanomaterials, such as silver nanoparticles, titanium dioxide ($TiO_2$) nanoparticles, and nano-sized carbon allotropes (nanotubes, nanofilms, graphene, and fullerenes or buckyballs) present interesting properties such as antimicrobial attributes, catalytic reactivity, and hardness. Because of enhanced properties

* Corresponding author.
*E-mail address:* lmarr@vt.edu (L.C. Marr).

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such as these, nanomaterials have been incorporated into a vast array of consumer products. Such products have been described previously as *"nano-enhanced"*, *"nano-enabled"*, *"nano-products"*, *"nanotechnology-based"*, *"nanotechnology-related"*, etc. In this work, we will describe them as "nanotechnology-enhanced" products.

Although many manufacturers' claims are not backed by sufficient evidence that products indeed contain nanomaterials, the production and use or misuse of some nanotechnology-enhanced products present opportunities for aerosolization of engineered nanomaterials in the indoor environment, and subsequently inhalation exposure to them, whether intentionally or incidentally (Abbott and Maynard, 2010; Vance et al., 2015).

The quantification of inhalation exposure—including workplace regulations—is typically based on the mass concentration of a compound. However, the mass metric may not be appropriate for nanomaterials. A negligible total mass of nanoparticles may contain high numbers of them that can nonetheless harm the respiratory and cardiovascular systems (Quadros and Marr, 2010; Hull et al., 2012; Beaudrie et al., 2013; Morawska et al., 2013; O'Shaughnessy, 2013). The following set of characteristics has been proposed to describe nanomaterials in toxicity, exposure, and fate and transport studies (Oberdorster et al., 2005; Grassian, 2008; Abbott and Maynard, 2010; Quadros and Marr, 2010):

- Nanomaterial characteristics: size, shape, chemical composition, crystallinity and crystal structure, porosity.
- Surface characteristics: surface chemistry, surface charge, surface area.
- Environmental characteristics: number and mass concentration (per volume of air), aggregation/agglomeration state.

This added complexity may require an expansion of traditional thinking about how to measure and predict inhalation exposure to engineered nanomaterials. This review assesses the current state of knowledge about inhalation exposure to airborne, engineered nanoparticles in the indoor environment by determining the most likely exposure scenarios and describing relevant studies published to date.

## 2. Potential exposure scenarios

As nanotechnology is expected to permeate all sectors and industries, there will be numerous opportunities for indoor exposure to aerosolized nanomaterials. Opportunities for exposure may occur during the production, use, and/or disposal of products in residential and commercial spaces. Because physical rather than chemical properties determine particle transport indoors, we expect the movement and deposition of aerosolized nanomaterials in indoor air to be the same as for natural and incidental particles of the same size, keeping in mind that nanomaterials are likely to be present as internally and externally mixed aggregates rather than as primary particles. Nanomaterials are likely to interact with other components within products (before emission) and then interact with other components in indoor air (such as semi-volatile organic compounds, SVOCs) after emission (Morawska et al., 2013).

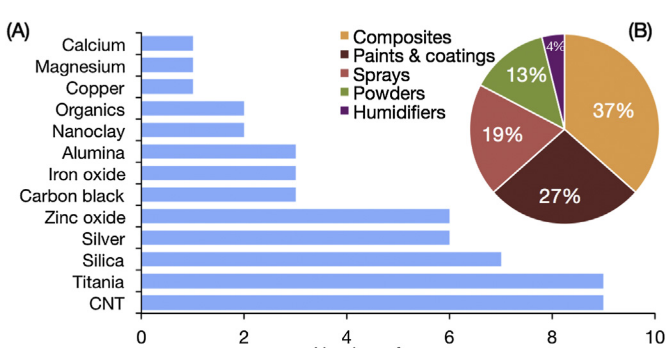


**Fig. 1.** Reviewed literature on the release of aerosols from use and wear-and-tear of products enhanced with engineered nanomaterials: (A) number of papers in which each nanomaterial composition was studied (some papers considered multiple nanomaterials); (B) the products or matrices in which the nanomaterials were applied.

### 2.1. Indoor sources

The current state of the art in the scientific literature on the release of aerosols indoors from nanotechnology-enhanced products is summarized in Fig. 1. We reviewed 31 studies, published over the past 7 years, that investigated the release of aerosols from use and wear-and-tear of products enhanced with engineered nanomaterials. Although unlikely to be comprehensive, this selection represents the papers we were able to find in the Web of Science and Google Scholar databases using the following search terms: release AND air AND indoor AND (nanoparticle OR nanomaterial OR nanofilm OR nanotube OR nanohorn OR nanowhisker OR nanotechnology). We did not include works on the release of nanomaterials during manufacturing or handling of unrefined nanomaterials.

In this limited number of studies, nanomaterials of a range of compositions were investigated, especially carbon nanotubes (CNT), $TiO_2$, silver, and zinc oxide (Fig. 1). Products investigated included composites, paints and coatings (or nanofilms), sprays, powders, and humidifiers (Benn et al., 2010; Quadros et al., 2013).

Researched composites consisted of a wide variety of nanomaterials embedded into a polymer, in many cases epoxy resin, matrix. The most commonly investigated composite nanomaterials were CNTs and silicon dioxide ($SiO_2$) (Köhler et al., 2008; Bello et al., 2010; Huang et al., 2012; Vilar et al., 2013) used to reinforce plastic laminates and, most frequently, epoxy resin. Silver (Zanna et al., 2010), alumina (Tsai et al., 2008), nanoclays (Raynor et al., 2012), silica (Pellegrin et al., 2009; Sachse et al., 2012), $TiO_2$, and zinc oxide nanoparticles (Busquets-Fité et al., 2013) were also studied in nanocomposites.

The Project on Emerging Nanotechnologies released a second generation of the nanotechnology Consumer Products Inventory (CPI) in October 2013 (Project on Emerging Nanotechnologies, 2013). This inventory lists consumer products that contain nanomaterials according to the manufacturer or a third-party source. Although it is not a comprehensive catalog of all nanotechnology-enhanced products that are available in the marketplace, this inventory is the largest available documentation of how nanotechnology has entered the worldwide marketplace, and it illustrates the broad applications of nanotechnology in consumer products. Since the implementation of a crowdsourcing tool, the CPI may be updated continually from the input of contributors (Vance et al., 2015).

An analysis of this inventory provides insight into the types of nanotechnology-enhanced consumer products that have the greatest potential to aerosolize engineered nanomaterials into indoor environments, such as homes, office buildings, schools, hotels, and hospitals. At the time of writing, the CPI listed 1802 products that claim to contain nanomaterials. Of all products listed, 10.8% (194 products) present the potential for aerosolization of nanomaterials and subsequent inhalation exposure during use or misuse. These are products that may produce aerosols or droplets (of any size) containing nanomaterials during their common-sense intended use, such as sprays (using manual pumps or in pressurized cans), hair dryers, and loose or compacted powders. The

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