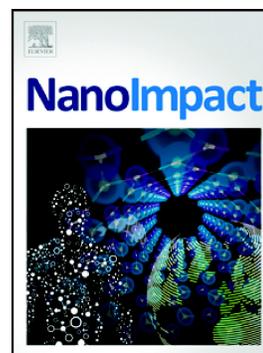


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Beatrice Salieri, David A. Turner, Bernd Nowack, Roland Hischier



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## Life cycle assessment of manufactured nanomaterials: Where are we?

Beatrice Salieri<sup>1</sup>, David A Turner<sup>1</sup>, Bernd Nowack<sup>1</sup>, Roland Hischier<sup>1</sup>

<sup>1</sup>Technology and Society Lab, Empa, Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, CH-9014, St. Gallen, Switzerland

### Abstract

For over a decade, life cycle assessment (LCA) has been recognized as a valuable tool for systematically evaluating the potential environmental impacts of manufactured nanomaterial (MNMs) during their complete life cycles. Evidence for its emerging role in the field can be seen in the increasing number of LCA studies that have been published in recent years. Since its emergence, several review articles have been published in the field, with these highlighting a number of shortcomings in the application of LCA to nanotechnology. Given the emerging, fast moving nature of the field, there have, however, been a number of developments (particularly in impact assessment) that have not previously been addressed. Here we present a review of progress in the field of LCA and nanotechnology in light of recent developments and consider whether previously identified shortcomings have been addressed by recent studies. Overall, the 92 studies considered in this review were generally found to lack completeness in terms of their coverage of MNM flows, a likely consequence of two key shortcomings in the application of LCA to MNMs: the lack of LCI data and the scarcity of MNM-specific characterization factors for toxicity-related potential impacts. We show that existing LCA studies of MNMs typically only account for flows of bulk (i.e. non-nano) substances, with releases of MNMs seldom considered. We discuss in depth the challenges of developing MNM-specific characterisation factors for (eco)toxicity impacts, which relate in particular to a lack of research concerning the exposure and effect of released MNMs. Overall, LCA studies of MNMs/nanotechnology are currently affected by a gap of knowledge regarding the quantities and risks of MNM releases into the environment during different life cycle stages. Based on our analysis, recommendations to LCA practitioners working in the field are provided, focusing on how they can ensure their studies are more complete, consistent and transparent.

**Keywords: manufactured nanomaterials; life cycle assessment; inventory analysis; impact assessment; characterisation factors; ecotoxicity**

### 1. Introduction

For certain industrial applications and consumer products, the use of manufactured nanomaterials (MNMs), defined as any intentionally manufactured material containing particles where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range of 1 to 100 nm-[1]) has numerous benefits compared to conventional, bulk materials, such as saving raw materials and/or energy [2]. However, there are still many unknowns related to MNMs, particularly concerning their potential environmental and human health impacts if they are released into the environment. Releases of MNMs can occur during any stage of the MNM life cycle, i.e. from the production of the MNM through the manufacturing of nanoproducts (i.e. products that contain

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