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Review

A system-of-systems approach as a broad and integrated paradigm for sustainable engineered nanomaterials

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HIGHLIGHTS

- System of systems approach to examine benefits and risks of ENMs was discussed
- The need for System of systems approach was emphasized
- The ENMs System of systems architecture and implementation plan were described

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ABSTRACT

There is an urgent need for a trans-disciplinary approach for the collective evaluation of engineered nanomaterial (ENM) benefits and risks. Currently, research studies are mostly focused on examining effects at individual endpoints with emphasis on ENM risk effects. Less research work is pursuing the integration needed to advance the science of sustainable ENMs. Therefore, the primary objective of this article is to discuss the system-of-systems (SoS) approach as a broad and integrated paradigm to examine ENM benefits and risks to society, environment, and economy (SEE) within a sustainability context. The aims are focused on: (a) current approaches in the scientific literature and the need for a broad and integrated approach, (b) documentation of ENM SoS in terms of architecture and governing rules and practices within sustainability context, and (c) implementation plan for the road ahead. In essence, the SoS architecture is a communication vehicle offering the opportunity to track benefits and risks in an integrated fashion so as to understand the implications and make decisions about advancing the science of sustainable ENMs. In support of the SoS architecture, we propose using an analytic-based decision support system consisting of a knowledge base and analytic engine along the benefit and risk informatics routes in the SEE system to build sound decisions on what constitutes sustainable and unsustainable ENMs in spite of the existing uncertainties and knowledge gaps. The work presented herein is neither a systematic review nor a critical appraisal of the scientific literature. Rather, it is a position paper that largely expresses the views of the authors based on their expert opinion drawn from industrial and academic experience.

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1. Introduction

Nanotechnology is of strategic importance to the United States and other countries around the world (Roco, 2007). Despite the fact that it is still in its infancy, the use of nanotechnology in a diversified number of products touches upon the quality of life of almost all stakeholders in society, the environment, and the economy (SEE) (El Naschie, 2006; Tolaymat et al., 2010). Thus, there is a unique opportunity and a great sense of urgency to build engineered nanomaterials (ENMs) that are sustainable. In this paper, sustainable ENMS are defined as materials that contribute value-added benefits (i.e., beyond economic gains) and produce minimal or no harm to the SEE system for a specified life expectancy to all constituents of the larger society, environment and economy (SEE) impacted by the raw ENMs and nano-enabled products and services.

Fundamentally, the process of developing ENMs involves altering and creating new physical–chemical properties for materials that are used to enhance products and generate new benefits (Sekine et al., 2013; Gebel, 2013; Chatterjee, 2008; Xu et al., 2012). Consequently, it is anticipated that ENMs are new chemicals with an unknown level of risk (regardless of the risk level, that is, negligible, low, moderate or high) to human health and the environment (FIFRA, 2009) and undetermined levels of potential benefits. Because of the uncertainties of knowledge regarding potential ENM benefits and risks, one ought to take into account two points when developing methodologies for the sustainable development of ENMs. First, there exists a body of knowledge generated over the years. This massive amount of information can be used to construct a broad and an integrated approach for the sustainable development of ENMs. Second, research gaps remain and may limit the full assessment of potential risks and benefits accrued (if any) from the produced ENMs (e.g., Marcoux et al., 2013; Misra et al., 2012). These data gaps should be addressed by drawing upon what is known of other materials and connect what applies to ENMs until further data becomes available. This equally applies to both benefits and risks, as they are two sides of the same coin.

Currently, research studies are mostly focused on examining effects at individual endpoints with emphasis on ENM risk effects. Less research work is pursuing the integration needed to advance the science of sustainable ENMs including the assessment of what constitutes value-added benefits beyond economic gains along the SEE life cycle trajectory. Therefore, the objective of this paper is to present the system-of-systems approach (SoS) as a broad and integrated vehicle to advance the science of sustainable ENMs within the context of sustainable solutions. An SoS is a system engineering methodology designed to solve complex problems (Jamshidi, 2008; Sage and Cuppan, 2001; Carlock and Fenton, 2001; Pinto et al, 2012; DeLaurentis and Sricharan, 2009; Gorod et al., 2008), with the goals in the case of ENMs to understand system behavior (e.g., via available data and simulation in the presence of gaps in knowledge) and to build responsible and sustainable decisions at different endpoints in the larger SEE system. At the heart of this approach is an architecture (Maier, 1998; Davendralingam and DeLaurentis, 2013; Butterfield et al., 2008) that can be formulated with varying levels of details to structurally connect all interactive entities. This will allow, among other things, to analyze the ENM SoS using environmental management tools such as those developed in environmental and chemical/material management (e.g., comprehensive environmental assessment (Davis, 2007)) and life cycle assessment (Karn and Aguar, 2007; Som et al, 2010) as well as system engineering methodologies such as hierarchical decomposition and multi-domain formulation for complex sustainable system design, agent-based modeling and simulation techniques, and system-of-systems engineering hierarchical framework for understanding SoS problem and solution (Alfaris et al., 2010; Azevedo et al., 2009; Bonabeau, 2002; DiMario et al., 2009). In light of the analyzed materials, one can design and anticipate the impact of sustainable harmonious solution among the SoS stakeholders.

To achieve the aforementioned objective, three specific aims are designed: Aim 1 — to present an overview of current approaches in the scientific literature for examining ENM implications and the need for a broad and integrated paradigm for sustainable ENMs; Aim 2 — to document the ENM SoS in terms of high-level architecture and governing rules and practices; and, Aim 3 — to discuss the implementation plan of SoS paradigm for sustainable ENMs. It must be kept in mind that the work presented herein is neither a systematic review nor a critical appraisal of the scientific literature. Rather, it is a position paper that largely expresses the views of the authors based on their expert opinion. While many useful reviews and critical appraisals have been enumerated in the different interdisciplinary sciences of ENMs, one ought to examine the larger picture beyond the risks of ENMs, including but not limited to, the overlooked area of whether or not ENMs truly contribute value-added benefits to the SEE constituents. The ultimate intent of this research is to synthesize the bits and pieces of information into a useful platform allowing us to understand behavior of the SEE system with respect to the joint benefits and risks of ENMs and render action-based decisions to advance the science of sustainable ENMs.

2. Current approaches for examining ENM implications and need for integrated studies

This section provides an overview of the current approaches in the scientific literature for investigating ENM implications and it also highlights the need for a broad and integrated paradigm to ensure the sustainable growth and development of ENMs (aim 1). Review of the literature on the current approaches for investigating ENMs implications indicates that the great majority of studies are experimental in nature with the goal to assess the negative implications and risk effects of ENMs at individual endpoints along the ENM trajectory and fewer analytic studies aim to examine ENM effects at more than one endpoint While experimental studies are expected to continue to close up the data gaps, equal emphasis should also be placed on analytic studies with the goal to understand the macro picture and render decisions on ENM risks and investigations on the positive implications of ENMs including value-added benefits.

Analytic approaches have been proposed in the scientific literature to examine ENM implications using a number of common tools such as comprehensive environmental assessment (Davis, 2007; Davis and Thomas, 2006), life cycle assessment (Karn and Aguar, 2007; Som et al, 2010; Hischier and Walser, 2012; Griffiths et al, 2013), and multi-criteria decision analysis (Linkov and Seager, 2011) (Fig. 1). These approaches behave as open systems and share common elements such as risk assessment and life cycle analysis, yet they may be different in scope, methods, and details and they do not holistically address ENM risks and benefits. Accordingly, researchers in the scientific literature (e.g., Linkov and Seager, 2011) have expressed the need for combining several of these techniques to fill in some of the stated limitations.

Table 1 presents examples of overviews of analytic studies in the scientific literature. Furthermore, recent systematic reviews on the subject are also documented in the table. The documented reviews and analytic