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Sustainability Evaluation of Nanotechnology Processing and Production

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This article discusses the current situation and challenges posed by nanotechnology from a sustainability point of view. It presents an objective methodology to evaluate the sustainability of nanotechnology products, based on a life cycle thinking approach, a framework particularly suited to assess all current and future relevant economic, societal and environmental impacts products and processes. It is grounded on a hierarchical definition of indicators, starting from 3D indicators that take into account all relevant dimensions of sustainability and support decision making, and continue to more specific 2D and 1D indicators that address specific issues. This article also identifies the key aspects that should be considered when assessing the sustainability of current and future nanotechnology products or where it performs a central role.

1. Introduction

Nanotechnology is currently a very important area of fundamental research and commercial development, with a potentially tremendous impact on the future of mankind. At its core, nanotechnology aims to manipulate, design, and control properties of matter at atomic or molecular scales (at length scales between 1 to 100 nm), with the purpose of creating new or improved materials to be used in a wide range of problems in different areas. Thus, nanotechnology represents a range of technologies. Despite the diversity of definitions depending on the application fields and objectives, all share and revolve around the same tenets: nanoscale size, unique properties, manipulation and control of matter at atomic scale.

Although nanosized materials are already extensively used in practice (e.g. in catalysis and in laundry detergents), nanotechnology refer normally to a more widespread use, in particular in day to day life applications. Designing products and processes taking into account sustainability (Mata et al., 2013, 2014a) is therefore of paramount importance to avoid unintended consequences of what may appear as beneficial when first introduced in the marketplace (Smith et al., 2004). In particular, adverse health and environmental effects are of special concern, due to the potential widespread dispersion of nanomaterials in nature, resulting from the exposure of humans and other living beings to novel materials which effects are not known, either in the short or in the long term. The main challenge comes from the fact that the essential data needed for a comprehensive sustainability evaluation are commonly not available (Helland et al., 2007). This is because life cycle based data on the properties, fate and transport in the environmental media, and health and environmental effects of nanoparticles require extensive and time consuming experimentation, in many cases requiring newer methods of detection and/or measurement suitable for nanotechnology.

Notwithstanding the limitations on the sustainability evaluation of nanotechnology-based products, there is still room for objective approaches that show which aspects are more relevant and should be considered as research priorities (Martins et al., 2007). Most of them are directly linked with the impacts of

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nanotechnology on the environment and human health. Semi-quantitative or qualitative choices between different products or processes incorporating nanotechnology may be done this way. A method for the sustainability evaluation, already used for other systems/products (Mata et al., 2012), which serves these purposes is presented in this article, with a focus on how it can be used in the nanotechnology area. Based on an extensive literature review, the several significant impacts (economic, societal and environmental) that can be considered when evaluating the sustainability of nanotechnology-based products are identified, taking into account the product life cycle, from which a set of sustainability indicators is selected and prioritized. Special attention is given to the identification of important gaps in our current knowledge that must to be accounted for in the near future to ensure the correct judgments and strategies for the development of this already important area are made. Also, specific challenges posed by nanotechnology are discussed from a sustainability viewpoint.

2. Sustainability and nanotechnology

2.1 Why address sustainability?

In the past, unsuspected health and environmental impacts have occurred due to the utilization of substances that offered solutions to many industrial and societal needs, for which the deleterious effects were not predicted. For instance, the introduction of tetraethyl lead as an antiknock compound in gasoline and CFCs as refrigerants did lead to significant societal benefits, until the ill effects started to reveal themselves, respectively, in serious health consequences and the ozone depletion potential. Other examples include asbestos, methyl tert-butyl ether, perfluorinated compounds, and polychlorinated biphenyls, among others. Sometimes it takes a long time before the adverse effects of such materials/products in nature and of the exposure of living beings become evident (Dinesh et al., 2012). It is therefore crucial to address the sustainability of a nanotechnology-based product at its emerging state, during R&D and before it is introduced in the marketplace, so that it fulfils its promises without any significant potential societal, economic and environmental impacts. Some of those issues are already taken into account by current legislation and/or regulation, such as REACH in Europe for new chemicals used in industry, and the authorization process of new active principles in pharmaceutical products. Yet, they just focus on specific aspects. A consistent approach is still lacking aimed to evaluate the sustainability of nanotechnology based products.

2.2 Sustainability evaluation based on life cycle thinking

Measuring and/or reporting sustainability is a complex task that should include explicitly all economic, environmental, and societal aspects relevant to the system under study (Martins et al., 2010). In practice, indicators are selected or developed, considering the product or process life cycle, and quantified using system data (Mata et al., 2003). Life cycle thinking is very useful when determining the “sustainability footprint” of nanotechnology-based products (Bauer et al, 2008), as concepts such as system boundaries definition and functional unit are relevant (Mata et al, 2005), and the life cycle inventory is a source of valuable data to calculate the indicators values (Mata et al, 2012). Also, as nanotechnology is still an infant field (Naidu et al., 2008), when a new product is being developed it is possible by design to better control and to minimize the environmental impacts throughout its life cycle (Morais et al., 2010a,b). Moreover, at the outset it is easier to incorporate inputs from stakeholders (Martins et al, 2007).

However, nanotechnology poses several challenges to the application of life cycle thinking framework to sustainability assessment. First, there is such a large variety of applications and nanomaterials that, in many cases, it is hard to define what relevant aspects that ought to be accounted for (Bauer et al., 2008). Second, one may need to evaluate alternative manufacturing technologies for the same product and/or function, or one may compare products with similar functions but using different nanotechnology-based materials approaches. In all cases, the specific process details must be available for the proper application of life cycle thinking. In particular, it is important to correctly define the system boundary, to decide which life cycle stages should be considered, and which data are needed. As stated before, toxicological data on nanoparticles must be available to address the main potential impacts of nanotechnology. Unfortunately, currently these data are largely unavailable for existing nanomaterials, making the calculation of potential environmental impacts difficult. Moreover, currently there is no complete life cycle assessment (LCA) on nanomaterials or nanotechnology reported in literature, but only a few studies present limited evaluation based on life cycle thinking. For example, Joshi (2008) used a life cycle approach to assess whether developments in nanoclay composites can improve the environmental sustainability of biopolymers, concluding that it results in lower energy use and greenhouse gas emissions than production of many common biopolymers and glass fibers.

Krishnan et al. (2008) developed a life cycle inventory of materials, energy and emissions, associated with various fabrication process systems used in manufacturing of modern microprocessors. These authors also evaluated upstream energy requirements associated with chemicals and materials using existing LCA databases and an economic input-output model. The results include a comprehensive data set and methodology to be used to estimate and improve the environmental performance of a broad range of electronics and other emerging applications involving micro and nano-scale semiconductor manufacturing.
Khanna et al. (2008) performed an LCA of carbon nanofibers production. Due to the absence of quantifiable data on human health and ecosystem impacts for these nanomaterials, the authors performed the environmental evaluation on a mass basis, comparing results with traditional materials. The energy consumption results showed that the manufacture of carbon nanofibers used 6 to 60 times more energy than aluminum, steel or polypropylene. However, these results are not representative of optimized process conditions. Healy et al. (2008) evaluated the environmental impact of three different processes for producing single walled carbon nanotubes using LCA. Although these authors acknowledged the current difficulties in evaluating the environmental and health impacts of the nanoparticles, they argued that the study can be seen as a benchmark for comparison among the competing processes.
Despite the limitations it needs to be acknowledged that in many situations the qualitative results obtained from a limited LCA study is valuable in defining current and future research needs in the fields of sustainability assessment for process and product development, and to communicate with the relevant stakeholders. For example, it is important to characterize how a nanomaterial is used. When the nanoparticles are used immobilized in a process or product, it may be assumed that they are not released to the environment, thus having no impact. However, for other products where nanoparticles are highly dispersed, or designed to be used on or even within the human body, more in-depth toxicological studies are crucial. Recognizing the deficiencies on risk and impact assessment, the European Commission made the inclusion of LCA studies mandatory in the project proposals to be funded by the European Union dealing with research and development of nanomaterials or nanotechnologies. The main goals are to increase the limited knowledge in the area, in particular the characterization and quantification of the potential environmental impacts of nanotechnology, and allowing a proper future development and industrial implementation of the research results, avoiding unforeseen impacts and easing the communication with all interested stakeholders, especially the general public. Consequently, it is expected a fast development of this area in the near future, as a result of the increasing importance given to LCA and the obligations placed in companies to consider and reduce the impacts of their products, services and processes through their entire life cycles, not just in the stages directly under their responsibility.

3. Methodology for evaluating the sustainability of nanotechnology

Different strategies for evaluating sustainability of a product or process have been proposed in literature. Among them, the framework proposed and developed by Martins et al. (2007), and applied for example by Mata et al. (2012), is a flexible, objective and rigorous methodology. It is based on life cycle thinking, and it has a sequential and iterative nature, as shown in Figure 1.

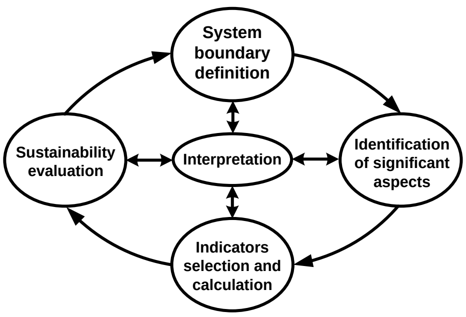

Figure 1: Methodology for the sustainability assessment of nanotechnology based products

First, one needs to define the system boundary for the study. Second, the most important environmental, societal and economic aspects associated to each product life cycle stage are identified. Third, the appropriate number of suitable metrics or indicators that best describe the system is defined, prioritize them in order to reduce the number of indicators to the minimum, this way avoiding duplicate information, and classify them in 3D, 2D or 1D (Martins et al., 2007). Fourth, the metrics and compare the sustainability of the current process or product relative to other(s) alternative(s) are computed. Finally, interpretation is placed in a central position relative to the other steps, as for any step a critical assessment should be performed, independently or combined with others. Also evident in Figure 1 is the iterative nature of this method, since as technologies evolve and more knowledge is acquired about the system it may be necessary to redefine the system boundaries, reevaluate or even define other indicators, eliminate indicators, change or improve calculation methods, or reassess previously made decisions.

3.1 System boundary definition

Since the sustainability evaluation is based on a life cycle thinking approach, all life cycle stages are considered, from the nanomaterials fabrication and supply, manufacture of products incorporating nanomaterials, use, maintenance, recycling and reuse, to final disposal, as shown in Figure 2. Depending on the particularities of the system and the study goals, the various stages should be considered in more or less detail, or even not accounted for, depending on the available data for example.

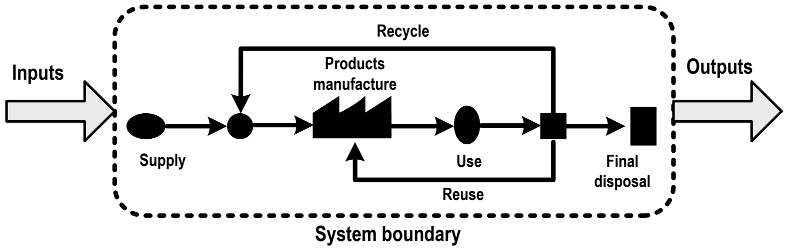

Figure 2: System boundary definition considering the product life cycle stages

3.2 Identification of the significant sustainability aspects

To identify the most significant environmental, societal, and economic impacts, one needs to study in detail the nanomaterial life cycle and perform a literature review. Also, interviews with the experts and people involved in R&D, and the nanofabrication and manufacture of nanomaterials-based products can be a source of helpful information. The indicators selection process can be done in different ways. For example, a matrix can be built listing all the life cycle environmental, economic and societal impacts deemed important for the sustainability assessment. Then, the most relevant sustainability metrics can be selected, classified and prioritized. This process is essentially a qualitative one, although as much as possible based on quantitative data. Some examples of potential impacts that might be considered when analyzing a nanomaterial's life cycle are presented in Table 1.

Table 1: Examples of potential environmental, societal, and economic impacts along a nanomaterial's life cycle

Manufacturing
Use of resources (materials, energy, water, and chemical substances)
Pollutant emissions, in particular of ultrafine particles (<100 nm)
Waste treatment and remediation
Workplace conditions in terms of health and safety
Employment and economic value generated
General use
Benefits to society and the environment
Product performance, service value to consumers
Reactivity and bioaccumulation
Ecological exposure and toxicity of nanoparticles to consumers
End-of-life disposal, reuse, or recycle
Recyclability
Solubility, bioaccumulation and persistence in environmental media
Ecological exposure and toxicity of nanoparticles

This procedure is supported by the identification and accounting of the main system's inputs/outputs (e.g. energy, water, materials, product, byproducts, wastewater, gas emissions, solid wastes, etc.), a process akin to make a life cycle inventory in a LCA study (Mata et al., 2001). Though here not just the environmental impacts are considered, but also the societal and economic impacts need to be included (Mata et al., 2014b). With the quantitative and qualitative information gathered, an inventory is constructed that can be used to calculate the selected sustainability metrics. This will result on a set of values that may be directly linked or not to specific life cycle stages of the product. If there is more than one type of nanomaterial performing the same function, each one should be analyzed individually in order to perform a comparison. One may start by comparing the nanomaterials manufacturing (one of the most critical stages in terms of impacts), and then expand the analysis upstream and downstream to include the remaining life cycle stages. Similar procedures can be followed for the comparison of processes and/or different technologies used for the same purpose.

3.3 Selection and calculation of sustainability indicators

The indicators deemed appropriate for the system under study are selected and prioritized, based on the information and data gathered in the previous steps. Then, the metrics dimensionality (3D, 2D, or 1D) should be determined (as shown in the example of Table 2). The prioritization is done based on system specific information, for reducing the number of metrics after their identification and selection. The number of metrics will also depend on the data available and study goals. The final set of indicators can be used for decision making, so they need to be correctly defined and calculated to ensure that the most appropriate decisions are made. Table 2 lists the potential indicators that can be applied for the sustainability assessment of nanotechnology products. It includes some standard indicators already considered by other authors (Martins et al, 2007) and already used in LCA studies of nanomaterials (Naidu et al., 2008), such as energy and material intensity that measure the production efficiency, regarded as sustainability indicators and applicable in most situations (Mata et al., 2013). Notice that the material intensity includes not only the raw materials but other chemicals needed for process operation or product manufacture, such as cleaning agents that are not included in the final product. Other indicators directly linked to nanotechnology may also be considered and classified (not listed here for lack of information).

Table 2: Classification of indicators according to their dimensionality in 3D, 2D, and 1D

Indicator	Environmental	Societal	Economic	Classification
Energy intensity (MJ/kg product)	Yes	Yes	Yes	3D
Material intensity (kg/kg product)	Yes	Yes	Yes	3D
Potential chemical risk (dimensionless)	Yes	Yes	Yes	3D
Potential environmental impact (dimensionless)	Yes	Yes	Yes	3D
Water use (m^3/ kg product)	Yes	No	Yes	2D
Global warming (kg CO_2-eq/kg product)	Yes	No	Yes	2D
Ultrafine particles emissions (kg/kg product)	Yes	No	No	1D
Wastewater generated (m^3/ kg product)	Yes	No	No	1D
Net cash flow generated (€/kg product)	No	No	Yes	1D
Direct employment (persons/t product)	No	Yes	No	1D

The list of indicators presented in the Table 2 is by no means applicable to all the nanotechnology based products or processes. Due to the specific nature of the manufacturing process and the unique nature of the nanoparticles, some indicators may have higher or lower dimensions, higher or lower priority. For example, on a local scale and for particular sectors of activity such as microprocessor industry, indicators like water consumption may be 2D or even 3D, as their processes are extremely water intensive. Although some general principles and guidelines can be formulated it is still necessary to study and include the particular details of any given process. After selecting the set of indicators, they should be quantified using data obtained as much as possible for the product or process under study. Only then product or process alternatives can be compared, or decisions regarding the process can be made. This evaluation process should be based as much as possible in consensual and widely accepted indicators, as it ensures that the decision making is more robust and less prone to controversy.

3.4 Sustainability evaluation and interpretation

Finally, the sustainability of the nanotechnology-based product is evaluated based on the computed indicators. If the purpose of the study is to compare among different alternatives, decisions concerning the most sustainable one can be made based on this evaluation, which can be complemented with the consideration of other issues, such as an economic analysis (Mata et al., 2014b).

4. Conclusions

This article analyses the current situation and main challenges regarding the sustainability evaluation of nanotechnology-based products. This analysis supports the conclusion that, albeit there is much hype and expectations concerning nanotechnologies, there are significant gaps in our knowledge that have to be addressed urgently in order to objectively evaluate the sustainability of nanotechnology-based products. In this article an objective methodology is presented for such evaluation that can be applied to a wide range of products. However, the lack of information about the impacts of nanomaterials in the environment and human health (in particular of nanoparticles) limits the calculation of the indicators, thus restraining its ability to support for example decision making. This is the result of the relative novelty of the field, and lack of knowledge about specific nanomaterials properties. Therefore, more research is needed in this area, for example to develop the respective materials safety data sheets (MSDS) and International Chemical Safety Cards (ICSCs). As more information is known, the more complete can be the sustainability evaluation. Other relevant aspect is the question of communication with the various stakeholders involved in the process, namely researchers, industrial developers and producers, final consumers, policy makers and the public in general. A lot of ground work has to be done to avoid problems in the utilization of nanotechnology and to facilitate the public acceptance of such products. Further complicating these questions is the distance existing between expectations and what nanotechnology has really accomplished until now, that makes an almost impossible task the decision making and assessing of what are the best choices from an environmental, societal and economic point of view.

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