LIFE CYCLE ASSESSMENT (LCA) OF NANOMATERIALS: A COMPREHENSIVE APPROACH

*Hidalgo, C.; González-Gálvez, D.; Janer, G.; Escamilla, M., Vázquez-Campos, S.**
Leitat Technological Center. c/ de la Innovació, 2 08225 Terrassa (Barcelona), Spain,
svazquez@leitat.org

Keywords: LCA; nanomaterials; modelling; environmental impact; human health.

ABSTRACT

LCA is a suitable method to assess the environmental performance of nanotechnology-based products, although challenges remain due to uncertainties and data gaps. LEITAT participates in different European projects, such as NANOMICEX, NANOPOLYTOX, NEXTEC, EUROTAPES and NANOSOLUTIONS, which contribute in filling in these gaps. Selected representative nanotechnology-based products were modelled, including all life cycle stages: raw materials, synthesis, functionalization, product manufacturing, use and end-of-life processes. When human health and ecotoxicological impact factors for released nanoparticles are integrated in LCA models, results show that their potential effect can be relevant in toxicity categories; thus such factors should be included to LCA approaches. Toxicity to workers is likely to be more relevant, so combined approaches of LCA and Risk Assessment (RA) are proposed.

INTRODUCTION

Nanomaterials (NM) and nanotechnology-based products are widely used nowadays in different applications. This trend has brought controversy due to the lack of data on their potential impact on human health and environment. Although LCA is considered as the best approach to assess the environmental behaviour of emerging technologies, currently the potential impacts of the released NM associated to human and environmental health are not yet introduced in LCA databases and several uncertainties and data gaps exist (Hischier, 2012). The main goal of applying LCA approaches in nanotechnology-based products is thus to derive characterization factors for NM using existing models as a starting point. Inventory and impact data could be included in LCA databases and impact methods to allow performing comprehensive LCA studies on nanotechnology-based products and their applications, comparing them to conventional materials, and providing the basis for future regulations and policies in this field.

LCA toxicity models are designed to evaluate toxicity hazards for the environment and the general population. However, human workplace exposure can be considerably higher than that occurring via the environment. Very little information is available on the risks of workers exposed to NM. In order to broad the scope and include safety and social issues in the sustainability assessment, for human toxicity category the impact for both workers and general population should be assessed combining LCA and RA methodologies (Grieger, 2012). This is the approach of NANOMICEX, which is aimed to apply LCA knowledge achieved in projects such as NANOPOLYTOX and the standardized LCA methodology to define working exposure scenarios and to perform a complete RA in all life cycle stages of ENM included in conventional materials (paints and inks).

MATERIALS AND/OR METHODS

A complete methodology has been developed in order to assess the life cycle of different types of nanotechnology-based products. The methodology used allows adapting the existing databases and impact assessment methods in order to include specific and new data of NM potential impacts. The study has been performed in accordance to the LCA ISO-framework (ISO 14040:2006 and ISO 14044:2006). Calculations have been done using SimaPro software, and taking as a base Ecoinvent Database and ReCiPe method. In the inventory phase resources used, energy, emissions, waste, and NM emissions to the environment were included. Research projects generate inventory data, especially related to NM releases and interactions. NM can be released to the environment during all their life stages and depends on their concentration in the product, the lifetime of the product, the way that the NM are incorporated in the final product, its use and disposal.

The ReCiPe Impact Assessment method has 18 midpoints indicators, which have a low level of uncertainty, and three endpoints indicators, aimed to do easier results interpretation but with a higher uncertainty: i) damage to human health (HH), ii) damage to ecosystem diversity (ED) and iii) damage to resource availability (Goedkoop, 2009). ReCiPe model does not contain characterization factors specific for nanoparticles. Within its set of impact categories, Human Toxicity and Freshwater Ecotoxicity were considered the most relevant categories in terms of the possible impact of released NM.

Models and factors for toxicity effects in LCA are based on the relative risk and associated consequences of NM and chemicals that are released into the environment. The derivation of these characterization factors requires taking into consideration the environmental and biological fate, human exposure, and the toxicological responses. The characterization factors for these categories have been estimated following the principles of the USEtox model (Rosenbaum, 2008), which is approved by UNEP-SETAC as the preferred model for characterization modelling of human and ecotoxicity impacts in LCIA.

The general equations to generate fate factors in the USEtox model are not directly applicable to NM. NM characteristics governing their fate (size, shape, porosity, agglomeration state, surface area, surface charge, composition, density, reactivity, etc.) have been considered in our studies in order to predict their environmental distribution.

Four nanocomposites were studied in NANOPOLYTOX. Release, exposure, fate and (eco)toxicity of NP were assessed in order to derive characterisation factors on freshwater ecotoxicity and human toxicity. Release and exposure were estimated based on the processes typology and data from literature. Fate was modelled adapting USEtox model and introducing the main physico-chemical characteristics of each nanoparticle, obtained from experimental data of the project and literature. For toxicity effect factors, ecotoxicity data were collected from experimental project data and literature; and oral and inhalation human toxicity data were collected from literature. Two scenarios were defined, a probable and a worst case scenario (which combine probable and worst case fate factors, toxicities and NM releases). The combination of fate, exposure and toxicity factors in USEtox proportioned the final characterisation factors. These factors were applied to NM release quantified in each stage in order to obtain their potential impact. These impact values were added to environmental impacts results from each process calculated with ReCiPe method.

RESULTS

NANOMICEX and the other projects cited are ongoing, therefore in this section only results of NANOPOLYTOX project are described although the approach for the rest of the projects are similar and advances in NANOPOLYTOX are serving as basis for ongoing projects. In NANOPOLYTOX, four nanocomposite materials were analysed. As a case example, main results for 3% MWCNT in polypropylene (MWCNT-PP) and 3% TiO_2 in polyamide (TiO_2-PA) nanocomposites are discussed in the following sections.

Environmental impacts were assessed at midpoint and endpoint level in order to see the relative contribution of the different life stages and the main impacting parameters. General distribution of all studied NM followed a similar scheme; in all production and transformation processes, electricity was the most impacting parameter. Due to energy consumption, climate change appeared to be the most relevant impact category at endpoint level, both on HH damage (84% for MWCNT; 83% for TiO_2) and ED damage (97% for MWCNTs; 95% in TiO_2). At endpoint level, characterization factors of freshwater ecotoxicity and human toxicity due to released NM were added to final results. In use stage, only the impacts from released NP were considered, with no impacts coming from other sources during the application of composites. Results for the defined worst scenario are shown in the tables 1 and 2.

Table 1. Endpoint categories at damage level for MWCNT-PP (1 kg). Worst case scenario

	HUMAN HEALTH (HH)		ECOSYSTEM DIVERSITY (ED)		RESOURCE AVAILABILITY	
	Stage contr	Value (DALYs)	Stage contr	Value (sps·year)	Stage contr	Value ($)
Synthesis MWCNT	5%	1.73E-06	4%	7.19E-09	3%	4
Composite MWCNT-PP	49%	1.70E-05	48%	8.03E-08	55%	82
Use	0%	7.21E-11	0%	4.64E-12	0%	-
Mechanical recycling	46%	1.60E-05	48%	8.07E-08	43%	64
TOTAL	**3.48E-05**		**1.68E-07**		**150**	
Relative contribution CNT released (all stages) /process	**Process 99%** **CNT released 1%**		**Process 99.997%** **CNT released 0.003%**		**Process 100%** **CNT released -**	

Table 2. Endpoint categories at damage level for TiO_2-PA (1 kg). Worst case scenario

	HUMAN HEALTH (HH)		ECOSYSTEM DIVERSITY (ED)		RESOURCE AVAILABILITY	
	Stage contr	Value (DALYs)	Stage contr	Value (sps·year)	Stage contr	Value ($)
Synthesis TiO_2	15%	2.53E-05	12%	7.76E-08	12%	47
Functionalisation TiO_2	29%	4.78E-05	20%	1.25E-07	22%	88
Composite TiO_2-PA	16%	2.65E-05	14%	8.48E-08	12%	47
Use	1%	9.72E-07	0%	4.41E-12	0%	-
Chemical recycling	39%	6.54E-05	54%	3.34E-07	55%	220
TOTAL	**1.66E-04**		**6.22E-07**		**402**	
Relative contribution TiO_2 released (all stages) /process	**Process 76%** **TiO_2 released 24%**		**Process 99.97%** **TiO_2 released 0.03%**		**Process 100%** **TiO_2 released -**	

DISCUSSION

In MWCNT-PP nanocomposite, mechanical recycling and composite synthesis are the stages with higher contribution in the three damage levels, whereas synthesis of NP (fluidized bed deposition) has lower impacts associated. Globally, TiO_2-PA composite has higher potential damage values in the three levels than MWCNT-PP, since particles are functionalized before application into composite (stage with relevant impacts) and waste treatment was chemical recycling, which has higher impacts than mechanical recycling. TiO_2 synthesis process (flame spray pyrolysis) has also higher impacts than MWCNTs synthesis, especially in Resources Availability category, due to a higher energy demand.

The relative contribution of released NM to environmental impacts was included at damage on HH and ED. Released MWCNT along life cycle contributed only to 1% on HH and 0.003% on ED. Higher contributions are found in synthesis process. In the case of MWCNT toxicity, effect on workers was also assessed for synthesis and nanocomposite stages with higher values, which corroborated the convenience of perform Risk Assessment in the different stages of the life cycle together to environment assessment. In the case of TiO_2-PA nanocomposites, the relative contribution of released particles is higher, being a 24% for human health damage and 0.03% in ecosystem damage indicator.

CONCLUSIONS

LCA approach for nanotechnology and nano-products can provide useful information about the main environmental impacts and benefits of this emerging technology. Prospective LCA approaches are needed and experimental data on characteristics and toxicity of nanoparticles coming from research projects should be included in LCA methodologies. Adapted exposure and fate modelling are needed in order to have complete results on the environmental performance of nano-products during all life cycle stages. LCA information should be used together with other methodologies such as RA to obtain a deep comprehension on the interactions of NM and the environment and the potential damage on environment and human health in all life cycle stages and exposure levels.

REFERENCES

Goedkoop M., Heijungs, Huijbregts M., de Schryver A., Struijs J., van Zelm R. (2009). ReCiPe 2008, A life cycle impact assessment method which comprises harmonised indicators at the midpoint and at the endpoint level. *First edition. Report I: Characterisation. VROM, 132 + 44 pp.*

Grieger K. D., Laurent A., Miseljic M., Christensen F., Baun A., Olsen S. I. (2012). Analysis of current research addressing complementary use of life-cycle assessment and risk assessment for engineered nanomaterials: have lessons been learned from previous experience with chemicals? *J. Nanoparticle Res. 14:958.*

Hischier R, Walser T. (2012).Life cycle assessment of engineered nanomaterials: state of the art and strategies to overcome existing gaps. *Sci. Total Environ. 2012 May 15;425:271..*

Rosenbaum R.K., Bachmann T.M., Swirsky Gold L., Huijbregts M.A.J., Jolliet O., Juraske R., Koehler A., Larsen H.F., MacLeod M., Margni M., McKone T.E., Payet J., Schumacher M., van de Meent D., Hauschild M. (2008). USEtox – the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Asess. (2008) 13:532.*