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Impacts of “metals” on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA)

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ABSTRACT

This paper looks into the differences and uncertainties in determining the impact of “metals”' emissions on human health, in Life Cycle Impact Assessment (LCIA). Metals are diverse substances, with different properties and characteristics, considered important in LCIA because of their toxicity to humans and ecosystems. First, we defined a list of the most significant metals in terms of impacts on human health. This was done according to precise criteria accounting for both physical and toxic properties of the metals. Second, we performed an LCIA on different key processes using various existing LCIA methodologies and including also USEtox: the recently developed consensus-model for LCIA. Last, we compared the results in relative terms using a *contribution analysis*. The analysis showed poor or no agreement between the methods: the relative contribution of each metal and of the metals in total to the total impact on human health changes greatly according to the LCIA method used. These differences are due mainly to the number of metals included in each method and to the technique used to calculate the characterization factors. Results obtained with USEtox show no apparent correlation with results calculated with other methods. At present time USEtox is recommended as the best model for LCIA on human toxicity, but mainly because of the large consensus behind it, because its uncertainties regarding metals are still high. The study gives a good and simple overview regarding the way different methods address the impact assessment for metals, and helps in the interpretation of LCIA results for actual LCA studies where metal emissions are involved.

1. Introduction

1.1. Background and objectives

This paper looks into the differences, and resulting uncertainties, in the estimated impacts of metals' emissions on human health, by nine individual Life Cycle Impact Assessment (LCIA) methods. Metals are diverse substances, with different properties and characteristics, considered important in LCIA because of their toxicity to humans and ecosystems (Finnveden et al., 2009; Gloria et al., 2006; Hauschild, 2005; Pennington et al., 2004; Rebitzer et al., 2004). The LCA, SETAC, and UNEP communities have often stressed the significance of the issue of metals and related impacts in LCIA (Jolliet et al., 2003b; Molander et al., 2004). In general, hazard classification for metals is a challenge as their inherent characteristics favour changing speciation, transformation and bioavailability within different environments, which again influence the severity of impacts exerted by these substances (Meister and Falck, 2008; OECD, 2008; Skeaff et al., 2008). In the specific field of LCIA, various impact assessment methodologies are available at present, but we believe that big differences exist in the way they address the human toxicity of metals, which should be taken in consideration when we analyse the results of an LCIA study. The occurrence of problems in such analysis, which are related to the varying magnitude of impacts of the individual metals, was in fact an inspiration for this paper. Previous studies tried to compare LCIA methodologies (Dreyer et al., 2003; Gloria et al., 2006; Pant et al., 2004), taking in consideration one or more of the impact categories and also the different methodological stages (characterization, normalization, weighting). In recent times, a high degree of consensus between scientists has been reached in the LCIA community in order to harmonize the way the methodologies deal with human toxicity (Hauschild et al., 2008). This consensus-building process resulted in recommended practices for characterization modelling of human toxicity, together with a new fate and exposure model for LCIA: USEtox (Rosenbaum et al., 2008), which harmonizes the existing

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models. However, big problems still remain when assessing human health impacts related specifically to metals' emissions in LCA. This is because of the high uncertainties in the modelling of fate and exposure, and in the definition of the impact, or mechanisms of action, exerted by the metals. Furthermore, LCA practitioners still face a double challenge when dealing with metal emissions: the choice of the appropriate method for their analysis (Does the chosen metal includes all/some/part of the metal emissions obtained from my inventory? Does it defines their impact on human toxicity, and how?) and the correct interpretation of the results (How important is their impact compared to other substances' impact? How uncertain is the result?). In this paper we analyse the impact category defined in most methods as "Human Toxicity" (the nomenclature is not uniform but the meaning is clearly the same), and we look at the role that metals play inside it. Particular attention is given to the characterization stage, which we think is the most critical. A comparison of methodologies including critical knowledge gaps is presented. Furthermore, science-based criteria for the inclusion/exclusion of metals in human toxicity-LCIA are proposed and suggestions for further research needs given.

1.2. Metals

In general terms, metals may be found in the lower-left side of the diagonal of semi-metals or metalloids (from Boron to Polonium) in the periodic table, which may act as both metals and non-metals. Metals are distinguished from non-metals by their capacity to lose electrons, forming positively charged ions, or Lewis acids, and by their speciation-dependent affinity for abiotic and biological interaction (D'Amore et al., 2005; Duffus, 2002). Several metals, such as iron, cobalt, copper, manganese, molybdenum, and zinc are needed at certain concentration levels by the human body, while others are toxic above the no observed adverse effect concentration level; such as lead, cadmium, mercury and arsenic, which have no beneficial influence on human health (Goyer, 2004; Jarup, 2003; Lindh, 2007). The toxic chemical speciation and/or concentration levels of metals are interesting, or of concern, in relation to ecosystem and human health aspects. Toxicity may be expressed through various potential mechanisms, such as interference with essential metals, and interactions with cellular macromolecules, such as phospholipids, nitrogen or sulphur within RNA or even DNA, and exerting oxidative stress within living organisms (Goyer, 2004; Shanker, 2008). Human activities like metal mining, smelters, shredder plants and waste depositing and incineration have increased the concentration of metals within the natural environment thereby increasing their mobilization to a level that exceeds that of their natural, and slowly occurring, life cycle (D'Amore et al., 2005; Nriagu, 1996). The existing man-made life cycle and the accompanying increased mobility of metals are influenced by environmental characteristics such as, e.g. pH, temperature, salinity, which again influence the speciation and bioavailability of these substances within the natural environment and in the end the human exposure to metals (Ljung et al., 2009).

2. Methods

2.1. Selection of metals

Reading through the different LCIA methodologies, we couldn't find any clear definition of the word "Metals", even if the term is often used to indicate a category of substances. Generally, "metals", as included in LCIA methodologies, conform to the following three criteria:

- Inorganic, in elemental or ionic form (and their fate can't be modelled according to existing risk assessment procedures using models for organic substances);
- Not degradable/persistent in the form they are in the environment (via bioaccumulation, bio magnification etc);
- In some ways toxic to humans, e.g. toxic via inhalation, or carcinogenic (toxicity to the ecosystem is a similar attribute, but we don't consider it in this paper).

Metals conforming to these criteria have also often been defined as "Heavy Metals", a definition that is poorly explicative and easily leads to misunderstandings (Duffus, 2002; Goyer, 2004), and will consequently *not* be used in this paper. Even if it would be methodologically appropriate to cite each time all the elements singularly, for brevity's sake, we refer to the substances analyzed in the paper simply as "*metals*".

Metals are characterized in LCIA in terms of their impact potential and assigned to a specific (midpoint) impact category, which can be defined as a "*Class representing environmental issues of concern to which various flows or actions tabulated as Life Cycle Inventory (LCI) results contribute, involving common or similar processes*"(Jolliet et al., 2003b). After this classification stage, characterization factors (*CFs*) are assigned to each emission in order to quantify its resulting impact. Regarding LCIA in general, *CFs* can be distinguished into two different types: the ones measuring a common impact mechanism (e.g. the environmental impacts of CO_2 equivalents, for all the emission with a potential greenhouse effect), and the ones measuring a similar impact, which can occur via different mechanisms (e.g. the human toxicity impacts measured as the carcinogenic potential for all the substances provoking cancer even if in different ways) (Jolliet et al., 2003b). It has been noted by several authors that the challenges of the hazard classification of metals are significant (Meister and Falck, 2008). For the same reason, and even though the criteria seem very diffuse, all LCIA methodologies use *CFs* of the second type for the quantification of toxic impacts. This approach allows for metals and other substances to be grouped together inside the same impact category (e.g. Human Toxicity–Carcinogens), even though they have varying toxic potency, target organs and mechanisms of action.

In this comparative study we consider: *Aluminium (Al)*, *Antimony (Sb)*, *Arsenic (As)*, *Barium (Ba)*, *Beryllium (Be)*, *Cadmium (Cd)*, *Chromium (Cr)*, *Chromium VI (Cr VI)*, *Lead (Pb)*, *Mercury (Hg)*, *Nickel (Ni)*, *Silver (Ag)*, *Strontium (Sr)* and *Thallium (Tl)* for the analysis. The selection follows these criteria:

(1) We decided here to prioritize the toxicity properties of the metals. So we considered only the substances that can be classified as "*Metals with no known beneficial effect for human health*" according to Goyer (Goyer, 2004). Chromium VI and Nickel are not part of such a list (Nickel is categorized in "*Metals with Possible Beneficial Effects*"). Despite this they are known for their carcinogenic effects on humans in higher doses (Goyer, 2004; Kabata-Pendias and Mukherjee, 2007) and, considering that in some LCIA methodology human toxicity has been measured in terms of carcinogenic potential, we included also them in the analysis.
(2) As a second criteria we used one of the scientific classifications for metals that have been proposed by Duffus (Duffus, 2002) inside the International Union of Pure and Applied Chemistry (IUPAC). In this case, Duffus' classification of metals according to their biologically significant chemical properties should fit the best to our purposes. It comprehends the three blocks of the periodic table: *s block*, *d block* and *p block*. Each of the above-cited substances belongs to one of these three blocks classifying their outer orbital electron characteristics and thereby (to a degree) their reactivity,
(3) They are available as emissions in the Ecoinvent database (Faist Emmenegger et al., 2007) in the atomic or ionic form.

It must be said that it is not clear, in the various LCIA methodologies, which are the criteria or the motivations for including/