Resources, Conservation & Recycling Advances 18 (2023) 200155

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Identification of most relevant variables and processes to assess the environmental impacts of remediation technologies along their life cycles: Focus on the waste management scenarios

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ARTICLE INFO

Keywords:
Life cycle assessment
Waste management scenarios, Contaminated sites
Remediation technologies

ABSTRACT

The application of Life Cycle Assessment (LCA) to remediation technologies is still not a consolidated practice and it is especially lacking in the assessment of the environmental impacts associated to the management of the waste produced during remediation. This study aims at addressing these methodological gaps by identifying the typologies of waste typically generated during the remediation of a contaminated site and classifying them according to the European Waste Catalogue (EWC) codes. Thereafter, the following steps are: (i) the identification of the waste management scenarios (WMSs) applicable to the identified waste typologies, (ii) the selection of Life Cycle Assessment processes that can be used to assess the impacts of the different WMSs and (iii) the quantification and comparison of the environmental impacts caused by the different WMSs applied considering hazardousness levels to which the same waste may belong in relation to its contamination levels and characteristics: inert, non-hazardous and hazardous waste (Waste Framework Directive 2008/98/EC). As results, a matrix reporting the classes and typologies of waste, their EWC codes, their different WMSs and the suitable LCA processes from the Ecoinvent database that can be applied to each EWC within a specific WMS, has been developed. Additionally, the comparative assessment of the impacts caused by the Ecoinvent processes applicable to the same waste typology within the same WMS has been performed to support the selection of the most appropriate WMS case by case.

1. Introduction

Soil consumption and degradation are relevant issues at global and European level. Historical contamination of soil caused by more than 200 years of industrialisation has an important role in soil degradation, considering that in Europe, there are around 2.8 million contaminated sites, of which only 650000 are registered (European Commission et al., 2018). Pushing towards contaminated sites remediation and re-use has thus become a major concern of European regional policies (Breure et al., 2018).

Indeed, soil is essentially a non-renewable resource, which performs many functions and delivers services vital to human activities and to ecosystem survival (European Commission et al., 2018). Remediation can bring contaminated soils to a new life, giving them back to the local community, by mitigating the risks posed to the environment and human health by the presence of contaminants in the environmental matrices (Hou and Al-Tabbaa, 2014). However, a remediation intervention, like any process, involves environmental impacts arising from the use of natural resources (raw materials, energy, water, etc..), waste production and emissions to the environment (Morais and Delerue-Matos, 2010). This must be considered in decision-making processes to select the most technically appropriate remediation technologies (Cadotte et al., 2007; Suèr et al., 2004). In addition, social and economic aspects must be considered simultaneously according to the sustainability principles (Cappuyns, 2013).

Since mid-to-late 2000s, growing interest for sustainable

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https://doi.org/10.1016/j.rcradv.2023.200155

remediation has emerged in several international and national organisations as well as in sectorial networks and forums (CL:AIRE and NICOLE, 2015; Common, 2020; SuRF Italy, 2020). These initiatives have now published a number of frameworks, standards, white papers, road maps and operative guidelines, such as the ISO 18,504:2017, which support stakeholders in the sustainability assessment of remediation technologies (Bardos, 2014; Rizzo et al., 2016). They are compared based on indicators that assess their sustainability, such as the consumption of mineral resources or energy, or the costs of implementation, etc. In fact, indicators are used to measure the performance of each remediation technology against the three pillars of sustainability: environmental, economic, and social (SuRF Italy, 2015). amongst these various aspects to be considered, the quantitative estimation of the environmental impacts along the life cycle of each assessed technology is crucial and is usually performed using Life Cycle Assessment (LCA) (Diamond et al., 1999). *LCA is a process to analyse and assess the environmental impacts of a product, process or activity over its whole life cycle* (Miettinen and Raimo, 1997). LCA allows for the identification of specific stages and processes where the most critical environmental issues are concentrated. Therefore, it can be used as a decision-support tool to develop a comparative analysis of different remediation technologies or to retrospectively identify more relevant aspects in terms of environmental impacts (Visentin et al., 2019).

In the scientific literature, many studies are available which present how LCA has been applied to remediation technologies for contaminated sites (soil and groundwater). Most of the reviewed studies performed an LCA considering the complete life cycle "from cradle to grave" (Amponsah et al., 2017; Blanc et al., 2004; Mauko Pranjić et al., 2018; Song et al., 2018) and in almost all of them, except for Page et al. (1999), LCA is performed *ante operam* and is used as a predictive tool to compare different remediation technology scenarios to be eventually implemented (Inoue and Katayama, 2011; Sparrevik et al., 2011; Toffoletto et al., 2005).

A standard approach to apply LCA to remediation activities is represented by the Product Category Rules (PCR) for soil and groundwater remediation measures, that has increasingly been used. PCR defines the principles and requirements for sector specific Environmental Product Declarations (EPD) that producers must follow when conducting LCA according to ISO 14,040.

According to PCRs, the life cycle of a remediation technology is divided into three different life cycle stages: the upstream processes, the core processes, and the downstream processes. The management of the waste produced by the remediation activities is part of the core processes. These wastes can be directly generated from the remediation activities as in the case of contaminated soil and water produced during dig & dump and pump & treat, or from the dismantling of the remediation plants and equipment. However, unlike the other core processes (i.e., remediation plant setup, external transport, electricity production, etc.) the environmental impact assessment of the management of the waste produced during remediation activities presents some criticalities since there are often not suitable LCA processes for their modelling. In fact, in most of the assessed studies, the management of remediation waste is not subject to in-depth analysis and often falls into over-simplified assessments that do not reflect the real generated impacts. This is because most of the studies are predictive and do not have sufficient inventory data to perform a comprehensive analysis that includes all necessary waste management considerations, or the assumption and simplifications are often not sufficiently explained and justified in the papers (Lemming et al., 2010). A more in-depth knowledge of this activity is essential to contribute to the positioning of waste management practices, which are critical in supporting policymakers and practitioners to transition towards a Circular Economy (Ranjbari et al., 2021).

Another critical aspect in the LCA studies related to waste management is the time aspect (Clavreul et al., 2012). Since these studies are typically carried out in ex-ante is difficult to properly evaluate the end-of-life stage, especially for long-live materials (e.g. building materials) (Lueddeckens et al., 2020). Therefore, temporal uncertainty associated to the assumptions done to define the future scenarios cannot be avoided as well as its impacts on the obtained results (Hosseinzadeh-Bandbafha et al., 2022). In addition, in most of the studies, the specific LCA processes used to model the final destiny of the waste under consideration and thus to quantify the impacts associated with waste management scenarios are not reported (Capobianco et al., 2018; Lesage et al., 2007; Suer and Andersson-Sköld, 2011). Most of the reviewed studies have been performed using the SimaPro software and the Ecoinvent database (Hou et al., 2016; Song et al., 2018; Sparrevik et al., 2011).

Accordingly, the assessment performed in this study has been conducted using these tools.

When approaching and selecting the waste management processes in SimaPro different types of landfills are modelled (PRé Consultants, 2016). However, these available landfills do not follow the classification as required by the current European legislation that identifies inert waste, non-hazardous and hazardous landfill Council Directive 1999/31/EC. Accordingly, the selection of the right type of landfill to model the waste produced during the remediation process is a challenging and demanding process which can affect the LCA results of remediation technologies.

The specific objective of this study is to identify the different typologies of waste produced during the remediation of contaminated sites, to classify them according to the European Waste Classification (EWC) codes and to identify the Waste Management Scenarios (WMSs) which can be applied to the identified waste typologies. In addition, this study aims to identify the LCA processes that can be used to assess, quantify and compare the environmental impacts caused by the different WMSs applied to the same waste typology.

2. Materials and methods

The developed approach for the assessment of the impacts caused by the management of waste produced during the remediation processes is reported in Fig. 1. It consists in the identification of: (i) the classes and typologies of waste produced during the contaminated sites remediation (e.g., class: Selective demolition Waste; typology: concrete) and their classification according to European Waste Classification (EWC) Codes (e.g., 170,101), (ii) the waste management scenarios[1] which can be applied to the identified waste typologies (e.g., Non-Hazardous waste Landfill for EWC 170,101) and (iii) the LCA processes (e.g. *Waste concrete {Europe without Switzerland}|treatment of waste concrete, inert material landfill*) that can be used to assess the impacts of the different waste management scenarios.

2.1. Identification of the waste classes and typologies, their classification according to EWC codes and the applicable waste management scenarios (WMSs)

To assess the impacts related to the management of the waste produced during remediation, it is first necessary to identify all possible types of waste resulting from remediation activities and the related possible disposal or recycling processes (i.e. the possible Waste Management Scenarios (WMSs)).

Waste classification involves determining if a waste is hazardous or not, through the Waste Framework Directive 2008/98/EC (Annex III) and identifying an appropriate classification code from the European

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[1] A waste management scenario is defined as a specific management system for a specific waste type (e.g., Inert waste landfill, incineration, etc.).

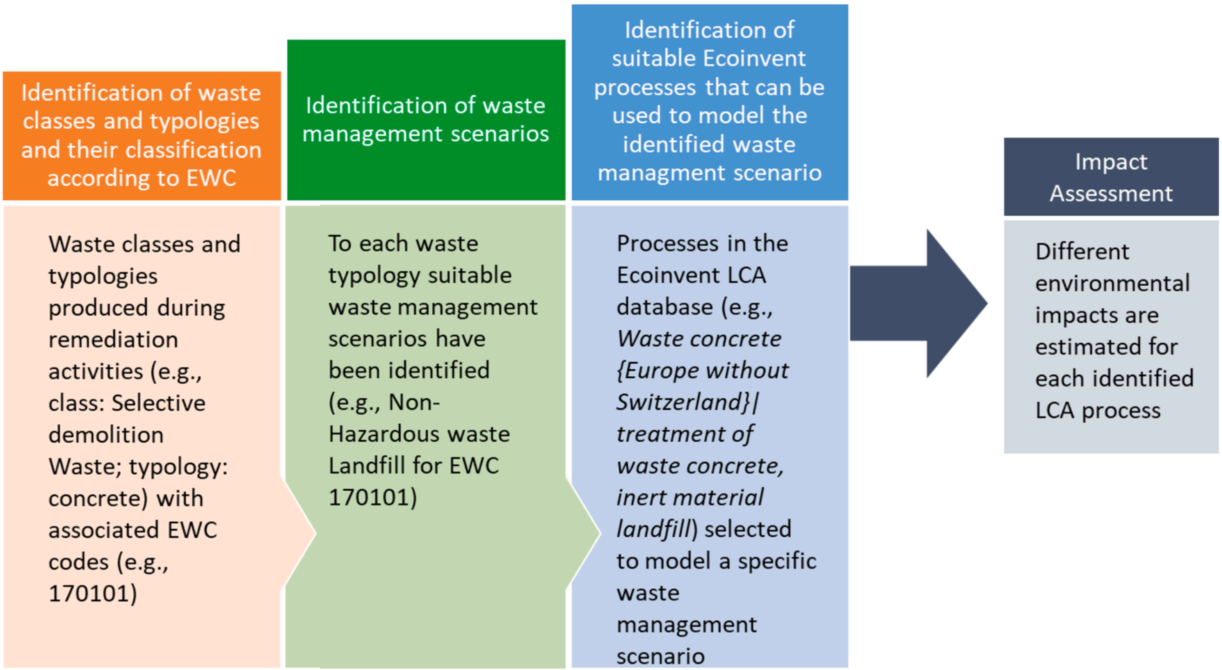

Fig. 1. The developed approach for the assessment of the impacts caused by the management of the waste produced during remediation processes.

Waste List (Commission Decision 2000/532/EC).

To this end, a preliminary assessment of the classes of waste produced during the remediation of the various contaminated sites managed by Eni Rewind[2] was performed, since this company has a variety of contaminated sites to remediate which is considered exhaustive. Indeed, the subsequent involvement of contaminated sites experts (i.e. practitioners) confirmed the selection which includes, as reported in Table 1: (i) selective demolition waste, (ii) soil and stones, (iii) leachates, (iv) desorption plant waste, (v) solid wastes from solid remediation, (vi) sludges from soil remediation/sludges from groundwater remediation.

In each waste class, different typologies of waste are included. To each of them, the correct EWC code was assigned, as required by the current European and Italian legislation.

Then, to each EWC code, possible waste management scenarios were associated according to the waste typology and hazardousness; they include: inert waste landfill, non-hazardous waste landfill, hazardous waste landfill and incineration, as reported in Table 1.

2.2. Identification of suitable Ecoinvent processes to model the identified waste management scenarios for each specific waste typology (i.e. EWC codes)

For each waste management scenarios identified in the previous step and according to the specific waste typologies they can be applied to, suitable processes available in the Ecoinvent database have been identified.

SimaPro, one of the most popular LCA software, has an advanced set of processes to model the different waste management systems but, as anticipated, it has no specific processes for each typology of waste produced during remediation. Moreover, it does not include a classification of landfills in accordance with the current European legislation. For these reasons, the available waste treatment processes have been deeply assessed to identify those that best represent the identified waste management scenarios and the related waste typologies (for each EWC code) (Doka, 2009, 2003).

Specifically, an in-depth assessment was carried out for all the processes that could model the WMSs (Waste Management Scenarios) for the different EWC codes reported in Table 1. This assessment included the construction of these processes (i.e., sub-processes included), the associated input data as well as the included activities, the geographical references, the involved technologies, the waste composition and the related emissions on the environment. The processes were selected from the Ecoinvent 3.6 database and the system model used was APOS, "Allocation at the point of substitution", following the attributional approach in which impacts are attributed proportionally to specific processes (Ecoinvent, 2020). Additionally, the geographical reference of the data was considered in the choice of processes, as they can refer to the whole world (global, GLO), to a region composed of several countries (e.g. Europe, RER), to a country (e.g. Switzerland, CH) or to a smaller area (e.g. a province) (Weidema et al., 2013). For this study, the "Europe without Switzerland" processes were first considered, as they are better suited to represent the European and thus the Italian context, alternatively, other geographical location were selected. All the suitable Ecoinvent processes identified for each EWC code and related WMSs are reported in Table 1.

2.3. Impact assessment

The ReCiPe midpoint method in the Hierarchist perspective (H) version was used to assess potential environmental impacts caused by the waste produced during the remediation processes. Two assessments were carried out to compare: (i) the outcome of different processes that can be used to assess environmental impacts of the same EWC code within a specific WMS (to identify the most suitable process to be used for modelling the specific waste within a specific WMS); and (ii) the environmental impacts of different WMSs for the same EWC code (to discuss and support the selection of the most sustainable WMS).

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[2] Eni Rewind, Eni's environmental company, is one of the major operators in the Italian remediation sector, managing around 3760 ha of land, about 65% of which fall within Sites of National Priority, and 2 million tons of waste. https://www.eni.com/enirewind/en-IT/home.html

Table 1
All possible classes and typologies of waste resulting from remediation activities, their EWC code and the applicable waste management scenarios (WMSs). In bold the most common waste generated during remediation processes, underline the recommended WMS for those wastes that have two possible WMSs for the same waste scenario while in italics the Ecoinvent 3.6 processes identified as the most suitable to model the specific WMS scenarios.

Waste classification			Disposal scenarios			
Waste Classes	Waste typologies	EWC codes	Inert waste landfill	Non-Hazardous waste landfill (sanitary landfill)	Hazardous waste landfill	Incineration
Selective demolition waste	**concrete**	**170101**	**I1, I2**	**NH1**	**n.a.**	**n.a.**
	wood	170201	n.a.	NH1, NH6	n.a.	n.a.
	plastic	170203	n.a.	NH1, NH4	n.a.	n.a.
	glass, plastic and wood containing or contaminated with hazardous substances	170204*	n.a.	n.a.	H1	H2
	bituminous mixtures containing coal tar	170301*	n.a.	n.a.	H1	H2
	bituminous mixtures other than those mentioned in 170301	170302	n.a.	NH3	n.a.	n.a.
Soil and stones	soil and stones containing hazardous substances	170503*	n.a.	n.a.	H1	H2
	soil and stones other than those mentioned in 17 05 03	170504	n.a.	NH1	n.a.	n.a.
Leachates	landfill leachate containing hazardous substances	190703*	n.a.	n.a.	H1	n.a.
	landfill leachate other than those mentioned in 19 07 02	190702	n.a.	NH1	n.a.	n.a.
Desorption plant waste	spend activated carbon	190904	n.a.	NH1	n.a.	n.a.
	wastes from gas cleaning containing hazardous substances	100118*	n.a.	n.a.	H1	H2
	wastes from gas cleaning	100119	n.a.	NH1	n.a.	n.a.
Solid wastes from soil remediation	**solid wastes from soil remediation containing hazardous substances**	**191301***	**n.a.**	**n.a.**	**H1**	**H2**
	solid wastes from soil remediation other than those mentioned in 19 13 01	191302	n.a.	NH1	n.a.	H2
Sludges from soil remediation/ Sludges from groundwater remediation	**sludges from soil remediation containing hazardous substances**	**191303***	**n.a.**	**n.a.**	**H1**	**H2, H3**
	sludges from groundwater remediation containing hazardous substances	**191304**	**n.a.**	**NH1, NH2**	**n.a.**	**n.a.**
	sludges from groundwater remediation containing hazardous substances	**191305***	**n.a.**	**n.a.**	**H1**	**H2, H3**
	sludges from groundwater remediation other than those mentioned in 19 13 05	**191306**	**n.a.**	**NH1, NH2**	**n.a.**	**n.a.**
Waste management scenario CODES	**Ecoinvent 3.6 processes associated to each waste management scenarios CODE**					
I1	*Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill*					
I2	*Waste concrete {Europe without Switzerland}| treatment of waste concrete, inert material landfill*					
NH1	*Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill*					
NH2	*Refinery sludge {Europe without Switzerland}| treatment of refinery sludge, sanitary landfill*					
NH3	*Waste bitumen {Europe without Switzerland}| treatment of waste bitumen, sanitary landfill*					
NH4	*Waste plastic, mixture {CH}| treatment of, sanitary landfill*					
NH5	*Waste polyethylene {CH}| treatment of, sanitary landfill*					
NH6	*Waste wood, untreated {CH}| treatment of, sanitary landfill*					
H1	*Hazardous waste, for underground deposit {DE}| treatment of hazardous waste, underground deposit*					
H2	*Hazardous waste {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration*					
H3	*Refinery sludge {Europe without Switzerland}| treatment of refinery sludge, hazardous waste incineration*					

n.a. = not applicable scenario according to current management practices.
* = hazardous waste.

3. Results

3.1. Waste classification, identification of WMSs (waste management scenarios) and applicable Ecoinvent processes

All the identified classes and typologies of waste resulting from remediation activities are reported in Table 1 along with the related EWC code and the waste management scenarios (WMSs) that can be applied to it. The most common typologies of waste produced during remediation activities are reported in bold. For each EWC code and WMS the suitable Ecoinvent processes were also identified and reported in Table 1.

Additionally, Table 1 shows the processes identified in the Ecoinvent database as suitable to model the different WMSs: inert waste landfill (I), non-hazardous waste landfill (NH), hazardous waste landfill and incineration (H). For the first two, the disposal processes "inert material landfill" and "sanitary landfill" were respectively identified, while for the disposal of hazardous waste (i.e. third and fourth WMSs) "confinement in underground deposits" and "incineration processes" were selected.

3.2. Impact assessment

3.2.1. First impact assessment: comparison of the impacts caused by different Ecoinvent processes used to model the same waste typology

In the following sections, the comparison of the environmental impacts caused by the different Ecoinvent processes selected for modelling a specific WMS for a single EWC is reported.

Specifically, the comparison involves the following processes which can be used to assess the same EWC as reported in Table 1: (i) I1 vs I2 to model EWC 170101 (concrete) within the inert waste landfill WMS; (ii) NH1 vs NH6 to model EWC 170201 (wood) within the non-hazardous landfill WMS; (iii) NH1 vs NH4 to model EWC 170203 (plastic) within the non-hazardous landfill WMS; (iv) H2 vs H3 to model EWC 191303* and EWC 191305* (sludges from soil remediation containing hazardous substances) within the hazardous landfill WMS; (v) NH1 vs NH2 to model EWC 191304 and EWC 191306 (sludges from groundwater remediation) within the non-hazardous waste landfill WMS.

3.2.1.1. I1 vs I2 to model EWC 170,101 (concrete) within the inert waste landfill WMS. Concrete is the most common inert waste in remediation processes. The first assessment compares the two processes potentially suitable for modelling the cement landfill scenario: (i) I1: Inert waste, for

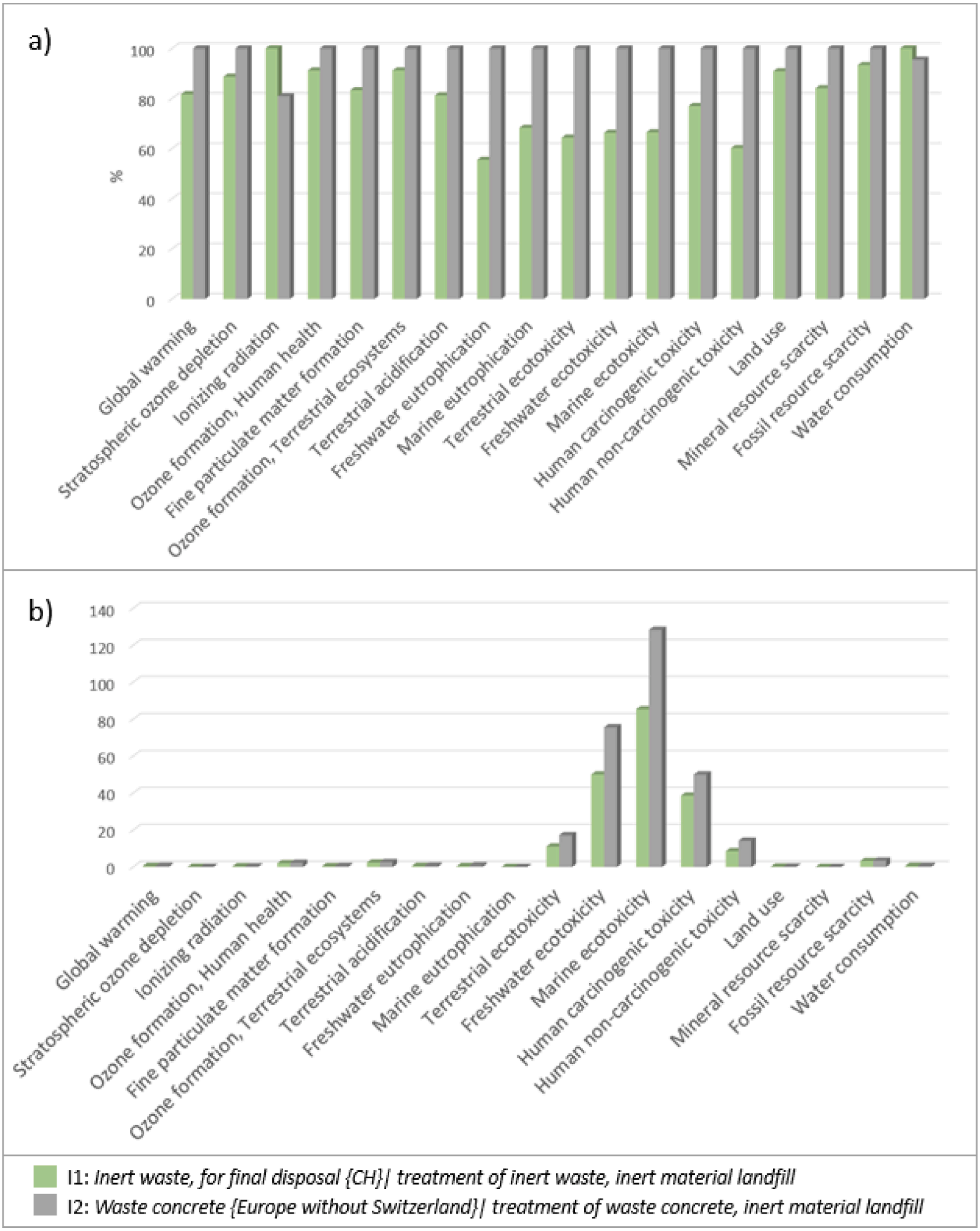

Fig. 2. LCA results for concrete (170101) disposal scenario in inert material landfill. a) Midpoint characterization of concrete disposal processes – I1 (green), I2 (grey), b) Midpoint normalization of concrete disposal processes – I1 (green), I2 (grey).

final disposal {CH}| treatment of inert waste, inert material landfill; (ii) I2: Waste concrete {Europe without Switzerland}| treatment of waste concrete, inert material landfill.

These two processes (I1 e I2) were selected to model the cement disposal scenario, which involves, as provided in Ecoinvent database, disposal in an inert waste landfill. The process “Inert waste, for final disposal treatment of inert waste, inert material landfill” is not available for the geographical location Europe without Switzerland.

Inert material landfills are landfills that can receive inorganic inert materials, the most abundant wastes which are landfilled in inert

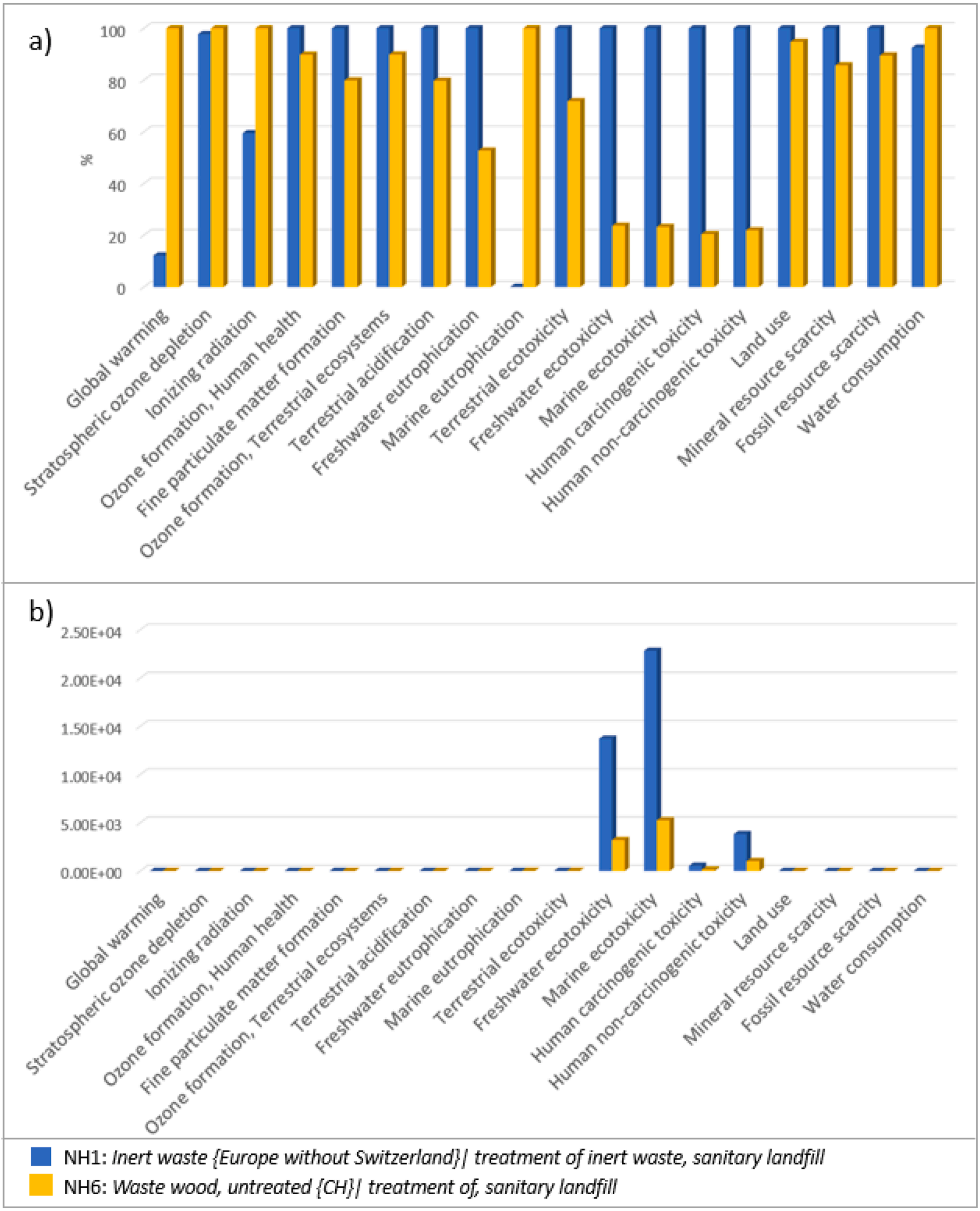

Fig. 3. LCA results for concreate (170101) disposal scenario in non-hazardous landfill. A) Midpoint characterization of wood disposal processes – NH1 (blue), NH6 (yellow), b) Midpoint normalization of concreate disposal processes – NH1 (blue), NH6 (yellow).

material landfills are excavation material and construction waste.

Characterized results of the midpoint level impact analysis for the two processes, I1 and I2, are shown in Fig. 2. Concrete management (I2) generally has higher impacts for most impact categories, exceeding 40% for the “freshwater eutrophication” and “human non-carcinogenic toxicity”, except for the "ionizing radiation" and "water consumption" impact categories where I1 outweighs I2.

The normalized midpoint results show that the most relevant impact categories are "marine ecotoxicity", "freshwater ecotoxicity", and "human carcinogenic toxicity", followed by “terrestrial ecotoxicity” and “human non-carcinogenic toxicity”. For all of them, I2 (i.e. concrete landfill disposal) is more impactful compared to I1.

Analysing the construction of the Ecoinvent processes in SimaPro, the difference between the impacts associated with these two processes is attributed exclusively to the geographical reference of the input data. In particular, the I1 process is characterized by input data (e.g. energy

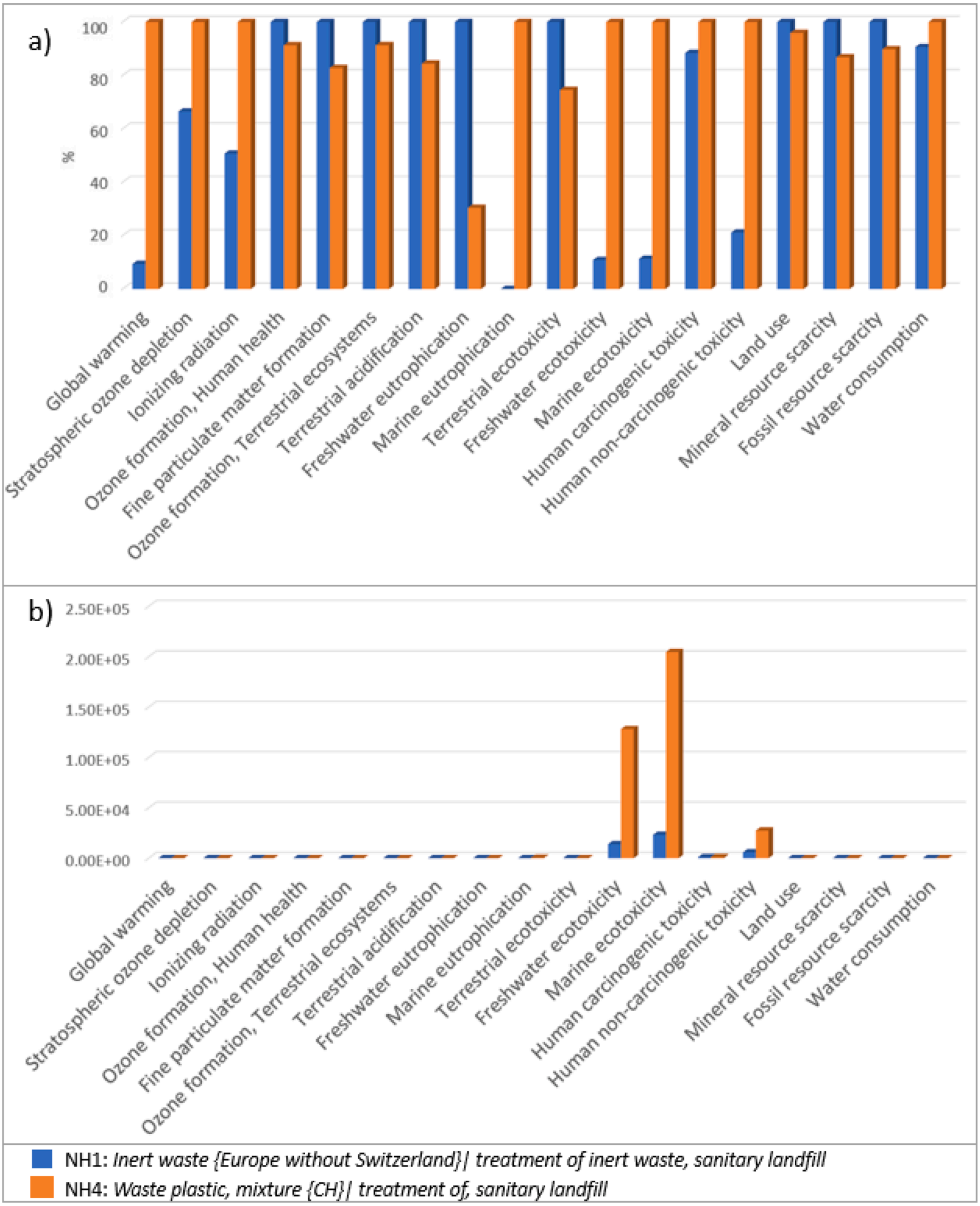

Fig. 4. LCA results for plastic (170203) disposal scenario in non-hazardous landfill. A) Midpoint characterization for plastic disposal in non-hazardous landfills – NH1 (blue), NH4 (orange), b) Midpoint normalization for plastic disposal in non-hazardous landfills – NH1 (blue), NH4 (orange).

mix, raw materials) specific to Switzerland, while the I2 process is constructed with a set of sub-processes mostly referring to the global level.

According to this evidence and in order to select a more precautionary LCA process, it is recommended to select the I2 process rather than the Swiss process I1.

3.2.1.2. NH1 vs NH6 to model EWC 170201 (wood) within the non-hazardous landfill WMS. The second assessment compares the two Ecoinvent processes suitable to model the environmental impacts caused by landfill disposal of wood waste (170201): (i) NH1: Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill; (ii) NH6: Waste wood, untreated {CH}| treatment of, sanitary landfill (a similar process is not available for the Europe without Switzerland geographical location).

Characterized and normalized impacts at the midpoint level are reported in Fig. 3.

As reported in Fig. 3 the process for wood disposal NH1 is characterised by higher values in most impact categories, particularly in those related to toxicity, compared to the NH6 process, as also normalized results demonstrate (Fig. 3b). At the same time, the results at the characterization level show that the NH6 process presents more relevant impacts for "global warming" and "marine eutrophication" categories. Considering the significant difference in the impacts generated by these processes, the selection of the NH6 process is specifically recommended to model landfill confinement for wood waste, while, the NH1 process can be adopted for a more conservative approach.

3.2.1.3. NH1 vs NH4 to model the EWC 170203 (plastic) within the non-hazardous landfill WMS. The third assessment compares the processes used to models the impacts caused by landfill disposal of plastic waste (170203). In this case the WMS considered is the non-hazardous waste landfill, modelled by NH1 and NH4 as reported in Table 1: (i) NH1: Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill; (ii) NH4: Waste plastic, mixture {CH}| treatment of, sanitary landfill (a similar process is not available for the Europe without Switzerland geographical location).

The ReCiPe midpoint methods have been applied and the characterized and normalized impacts at the midpoint level are shown in Fig. 4.

As reported in Fig. 4, the process for plastic disposal, NH4, is the most impacting for 9 out of 18 impact categories. The impact categories where NH4 presents much greater impact than the NH1 process are: "marine eutrophication", "global warming" and the impact categories related to toxicity. The normalized results indicate that the categories with the most significant impacts are "marine ecotoxicity", "freshwater ecotoxicity", and "human non-carcinogenic toxicity". The most impacting process is plastic-specific, due to the high energy consumption associated with this process. Since the NH1 process refers to general inert waste and given the difference in the impacts generated by these two processes, it is recommended to use the NH4 process to model the non-hazardous plastic management scenario.

3.2.1.4. H2 vs H3 to model the EWC 191303 and EWC 191305* (sludges from soil remediation containing hazardous substances) within the hazardous landfill WMS.* The fourth assessment compares the Ecoinvent processes selected for the incineration of sludges from soil remediation containing hazardous substances.

In order to model the incineration scenario for this waste (191303 and 191305: sludges from soil remediation containing hazardous substances), the following two Ecoinvent processes were identified, as reported in Table 1. The difference between these two processes is mainly due to the waste composition. For H2 process a generic hazardous waste is considered, while for H3 process a refinery sludge is involved. Moreover, these two processes provide a different residual waste, which is higher for H2 process than for H3. In particular, for H2 process the residue, which is landfilled after inertisation, is almost 19% by weight of the initial waste. While for H3 process the residue is less than 1.5%.

The ReCiPe midpoint methods have been applied and the obtained results are reported in Fig. 5. The characterized results highlight that H3 is more impactful then H2 for 10 out of 18 impact categories.

For the other 8 impact categories, H2 presents higher impacts than H3, in particular for "human carcinogenic toxicity" and "ionizing radiation" categories. Moreover, the normalization results show a greater contribution in the impact due to the H2 process, specifically for "human carcinogenic toxicity".

The comparison presented in Fig. 5 highlights that the processes applicable to hazardous waste present significant differences in terms of generated impacts and they cannot be used alternatively. This is mainly due to the higher consumption of energy required for sludge incineration, modelled by the H3 process. It is therefore recommended to keep the process H3 as the default scenario for the incineration of hazardous sludge instead of the Ecoinvent process related to the incineration of a generic hazardous waste (H2).

3.2.1.5. NH1 vs NH2 to model the EWC 191304 and EWC 191306 (sludges from groundwater remediation) within the non-hazardous waste landfill WMS. This last assessment compares the Ecoinvent processes used to models the impacts caused by landfill disposal of sludges from groundwater remediation.

The Ecoinvent processes selected for the landfilling of this waste (191304 and 191305: sludges from groundwater remediation) are: (i) NH1: Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill; (ii) NH2: Refinery sludge {Europe without Switzerland}| treatment of refinery sludge, sanitary landfill.

The ReCiPe midpoint method have been applied and the characterized and normalized impacts at the midpoint level are shown in Fig. 6.

As reported in Fig. 6, the process for sludge disposal NH2 is the most impacting for all impact categories. The normalized results indicate that the categories with the most significant impacts are "marine ecotoxicity", "freshwater ecotoxicity", and "human non-carcinogenic toxicity". The most impacting process is sludge-specific, due to the high energy consumption associated with this process. Since the NH1 process refers to general inert waste and given the difference in the impact generated by these two processes, it is recommended to use NH2 to model landfill disposal of sludges from groundwater remediation.

3.2.2. Second impact assessment: comparison of the impacts caused by different Ecoinvent processes used to model different WMS for the same EWC

In the following sections, the impacts caused by the different Ecoinvent processes selected for modelling a specific waste typology disposed according to different WMSs are compared in order to support the selection of the most sustainable WMS for that specific waste typology in an ex-ante perspective.

Specifically, the comparisons involve the following processes reported in Table 1.

3.2.2.1. I1 and I2 vs NH1 to assess the impacts of EWC 170101. This analysis involves the comparison of WMSs related to inert waste landfill and non-hazardous waste landfill for concreate disposal. Inert waste landfill disposal can be modelled with two different processes, one for a generic inert waste (I1) and another one specific for concreate waste (I2). Instead, the non-hazardous waste landfill disposal is modelled with a generic non-hazardous waste process (NH1). In Fig. 7 the results of this analysis are reported. The difference in the impacts generated by inert material landfill disposal (I1 and I2) and non-hazardous landfill disposal (NH1) processes is evident. At the characterization and normalization level, the NH1 process has the highest environmental impacts for all impact categories, while between the I1 and I2 processes the concreate-specific I2 process presents higher impacts than the I1 process.

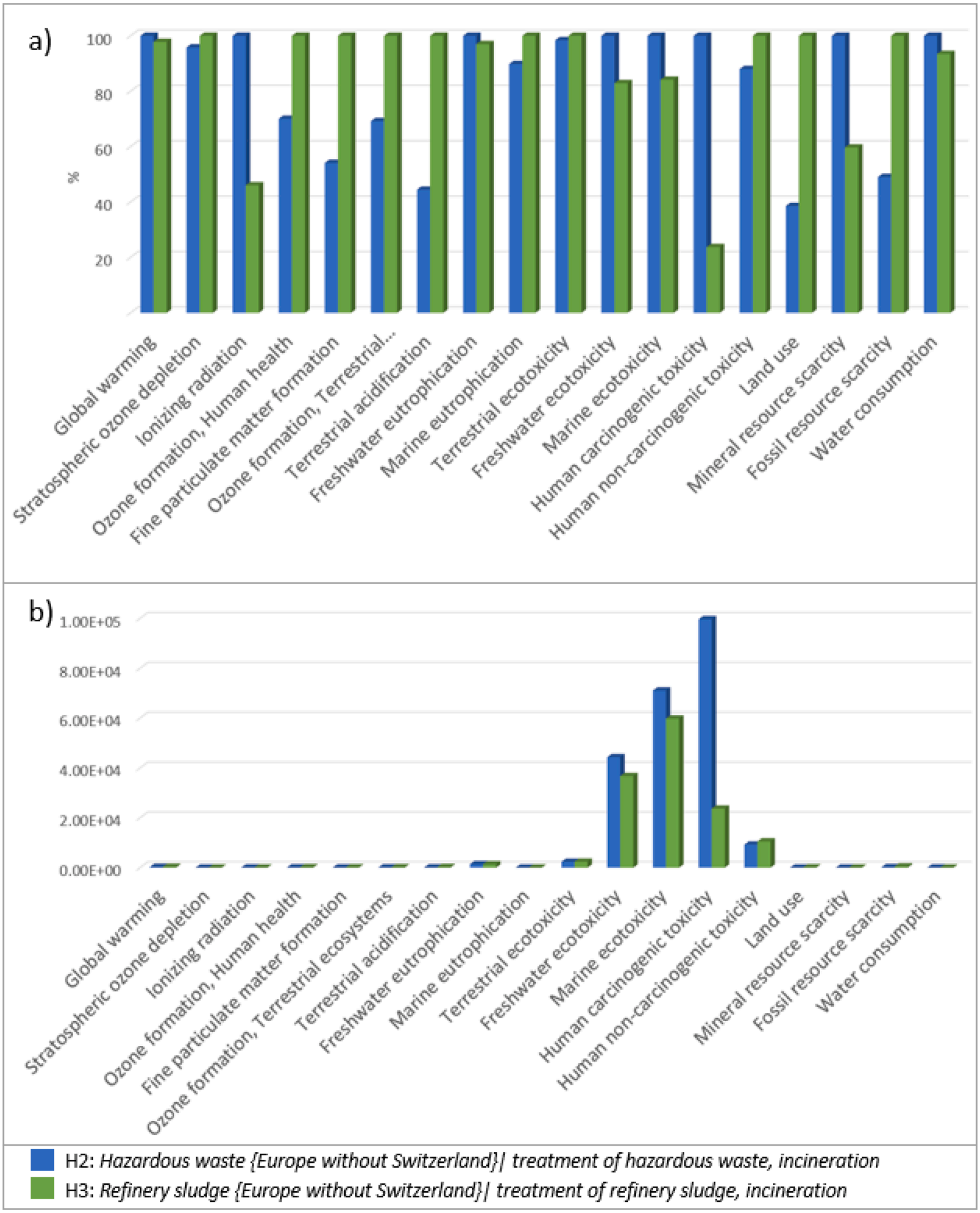

Fig. 5. LCA results for the hazardous waste management scenarios. A) Midpoint characterization of hazardous waste disposal processes – H2 (blue), H3 (green), b) Midpoint normalization of hazardous waste disposal processes – H2 (blue), H3 (green).

3.2.2.2. H1 vs H2 and H3 to assess the impacts of EWC 191303 and 191305*.* The following analysis involves a comparison of WMSs for hazardous sludge, relating to hazardous landfill disposal and incineration. Hazardous landfill disposal is modelled with underground deposit (H1), while incineration can be modelled with two different processes, one for a general hazardous waste (H2) and one for a hazardous sludge (H3). Fig. 8 (a and b) shows the comparison of these three processes.

Characterized results show that for all impact categories, except for “land use” and “mineral resource scarcity”, the scenario related to the waste confinement in underground deposit (H1) determines lower environmental impacts.

Between the two incineration processes (H2 and H3) there is an evident variability in the impacts generated for the different impact categories. The difference in these two processes is more apparent in some impact categories. Specifically, the one specific for sludges incineration is more impactful for the “fine particulate formation”,

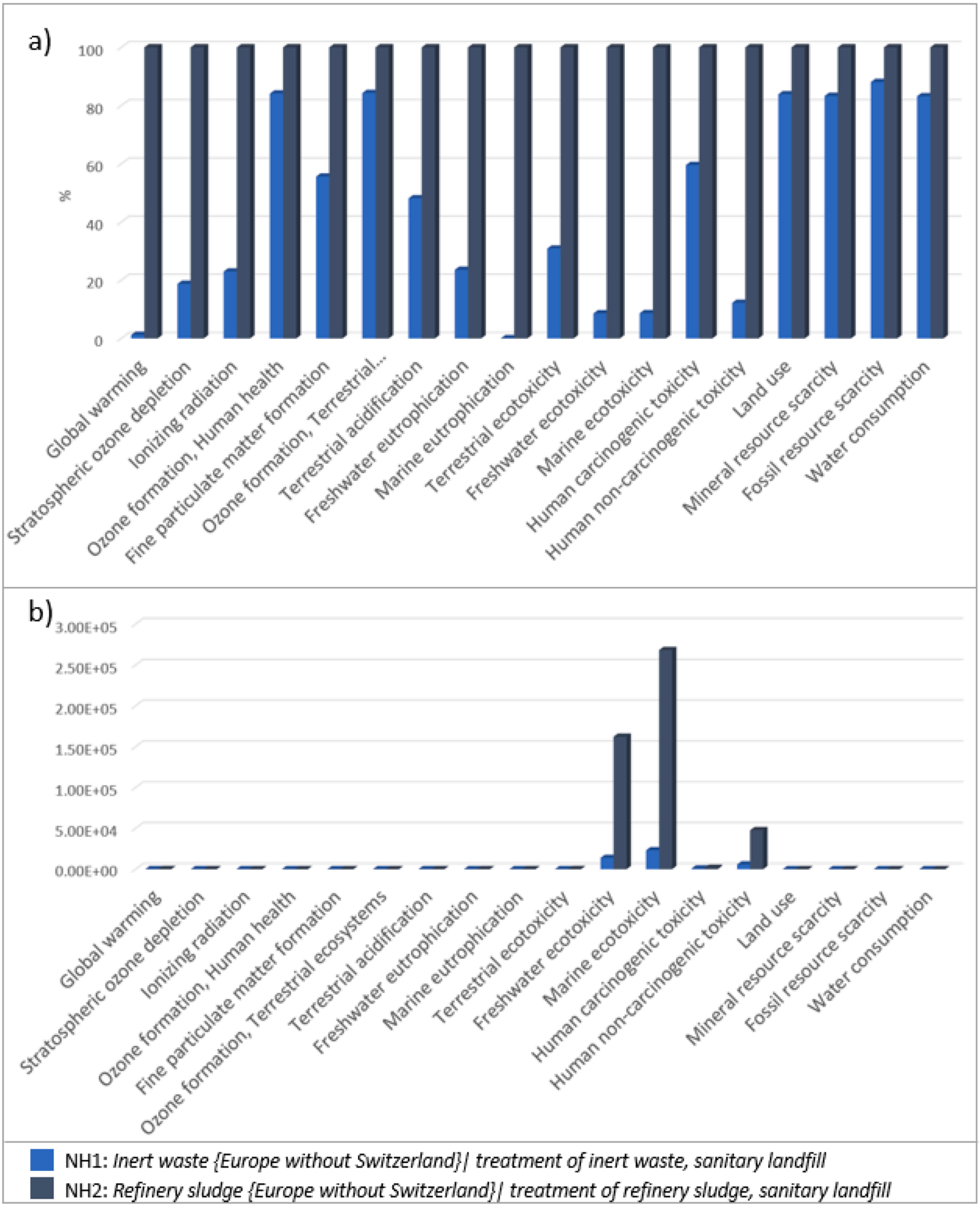

Fig. 6. LCA results for the non-hazardous waste management scenarios. A) Midpoint characterization of non-hazardous waste disposal processes – NH1 (blue), NH2 (dark blue), b) Midpoint normalization of non-hazardous waste disposal processes –NH1 (blue), NH2 (dark blue).

"terrestrial acidification" and "fossil resource scarcity", while the sludges incineration process has greater impacts for the following categories: "ionizing radiation", "human carcinogenic toxicity" and "water consumption".

The midpoint normalized results shows that the most impacted categories are "human carcinogenic toxicity", "marine ecotoxicity" and "freshwater ecotoxicity". In particular, the most impactful process is incineration, mainly due to the high associated energy consumption.

4. Discussion

This study follows from an in deep literature review of LCA studies on remediation technologies, which showed that the management of remediation waste often involves over simplified evaluations that do not reflect the real extent of the overall impacts resulting from the technology application. This lack is mainly due to the predictive nature of the analysed studies and therefore the lack of inventory data needed to

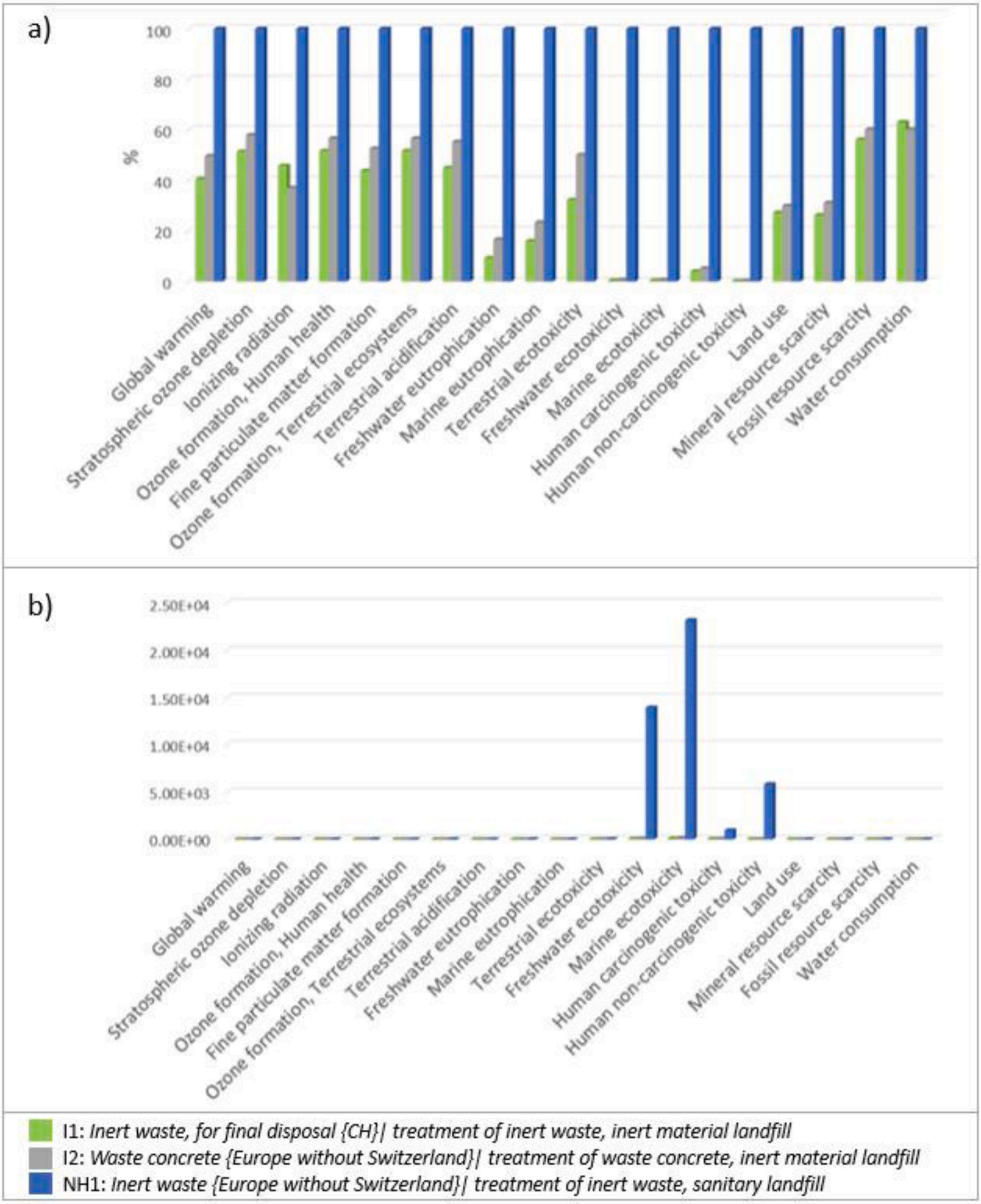

Fig. 7. LCA results for the WMS comparison for concreate waste. a) Midpoint characterization of inert waste landfill processes - I1 (green) and I2 (grey), vs non-hazardous waste landfill – NH1 (blue), b) Midpoint normalization of inert waste landfill processes - I1 (green) and I2 (grey), vs non-hazardous waste landfill – NH1 (blue).

make a complete analysis including all the necessary considerations in terms of waste management (Suer and Andersson-Sköld, 2011). Moreover, in most of the available LCA databases, like for example Ecoinvent, landfill classification for different waste (i.e. inert, non-hazardous and hazardous) according to the current European legislation is not available. Therefore, it becomes quite difficult to identify the most suitable LCA processes to be used to properly model waste management scenarios (Obersteiner et al., 2007).

To face this challenge, the research activity presented in this paper allowed to transparently and systematically support the assessment of the impacts caused by the management of wastes produced during remediation activities.

This led to the provision of Table 1, i.e. a matrix with the most relevant classes and typologies of waste resulting from remediation

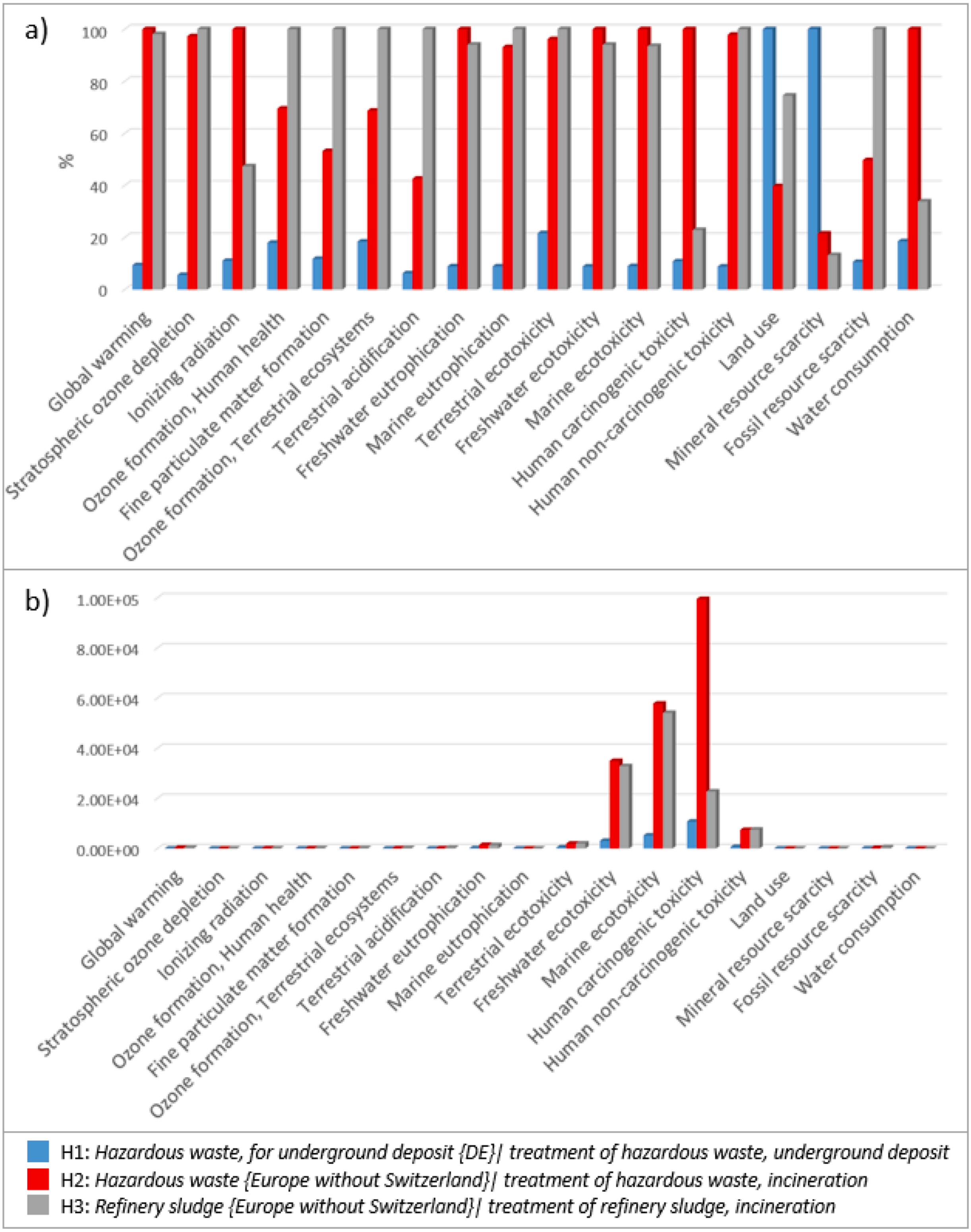

Fig. 8. LCA results for the WMS comparison for hazardous sludges from soil remediation (191303*) and from groundwater remediation (191305*). a) Midpoint characterization of underground deposit for hazardous waste - H1 (light blue) vs incineration for hazardous waste - H2 (red) and incineration for hazardous sludge waste - H3 (grey), b) Midpoint normalization of underground deposit for hazardous waste-H1 (light blue) vs incineration for hazardous waste - H2 (red) and incineration for hazardous sludge waste-H3 (grey).

activities, the related EWC code and the waste management scenarios (WMSs) that can be applied to each specific waste typology (i.e. EWC). Additionally, for each EWC resulting from remediation activities the suitable Ecoinvent processes are reported. This matrix can be used by academia and practitioners to identify possible WMSs for the waste resulting from remediation activities and the Ecoinvent processes that are more suitable to model them within a LCA study. Additionally, the comparative assessment of the impacts caused by the Ecoinvent processes, which can be applied to the same waste typology within the same WMS (e.g., I1 vs I2 to model the EWC 170,101), allowed to understand the differences, in terms of environmental impacts, and the causes of the identified differences by assessing the construction of the Ecoinvent processes. This allowed to suggest the Ecoinvent processes that best represent the specific typology of reclaimed waste in a LCA study within each identified WMS.

The life cycle impact assessment was conducted using the ReCiPe LCA method at the intermediate level. The characterized and normalized results enabled the comparative assessment of the different identified LCA processes. General consideration can be derived from this study, which are presented as follows. At both levels of assessment, a significant difference was observed in the environmental impacts generated by the assumed scenarios. This is partly related to the geographical representativeness of the identified processes. In particular, the processes compared in this study refer mostly to inventory data that have a Swiss ("CH") and European ("European without Switzerland") geographic location. European processes generally have higher impacts than the corresponding ones for Switzerland. This can be attributed solely to the geographic reference of the inventory data, while the construction of the processes appears to be the same. Indeed, the "European without Switzerland" geographic location considers wider application contexts including those characterised by less restrictive environmental regulations (Doka, 2009). This result therefore leads to the consideration that when a Swiss process is selected, since the European equivalent is not always present, a possible underestimation of the final impact generated must be considered in case of European-based assessments. Another interesting finding emerged during the evaluation of the normalized results, which deserve further investigation. It was indeed observed a greater impact on the midpoint indicators associated with damage to human health, such as ecotoxicity (in freshwater and marine environments) and human toxicity (carcinogenic and non-carcinogenic). This information could be of great interest to stakeholders and be relevant in a potential engagement process. Moreover, the results of the comparison of the environmental impacts caused by a specific waste typology disposed in different WMSs can be used, in an ex-ante perspective, as a tool to support more sustainable waste management practices.

Thanks to the second assessment, it was possible to choose the less impactful waste management scenario in a more conscious way, evaluating for each specific case the disposal and/or recovery alternative that implies lower environmental impacts.

The results of this analysis set the stage for future studies aimed at modelling both new processes that can correctly describe the typology of waste for which a specific Ecoinvent process is not available, and additional WMSs not considered in this analysis because less relevant in terms of produced environmental impacts, such as for example recovery WMSs which assess the recycling of concreate, wood, plastic and other materials produced during remediation. As final remark, this approach of evaluating waste generated by remediation sites could support the difficult, but important, definition of a correspondence between the EWC codes defined at European level and the waste typologies present within Ecoinvent.

5. Conclusions

This study investigated how to model, within LCA, the potential environmental impacts caused by managing wastes produced during the remediation activities carried out in contaminated sites. As main result, a transparent and systematic method was developed which facilitate ex-ante LCA of remediation waste and could guide waste management practitioners towards more sustainable practices.

More specifically, the proposed method involves identifying the different typologies of waste produced during the remediation of contaminated sites, classifying them according to the European Waste Classification (EWC) codes, identifying the Waste Management Scenarios (WMSs) which can be applied to the selected waste typologies, and finally choosing the most suitable LCA processes that can be used to assess, quantify and compare the environmental impacts caused by the different WMSs applied to the same waste typology.

The application of this method is currently constrained by the limited amount of waste management processes included in existing LCA databases which are also not aligned with the current European waste legislation.

Additional efforts in the development of LCA waste management processes could allow a more correct and complete evaluation of environmental impacts of downstream processes in remediation activities as well as in other industrial sectors.

CRediT authorship contribution statement

M. Menegaldo: Methodology, Formal analysis, Investigation, Conceptualization, Validation, Writing – original draft, Writing – review & editing, Visualization. **L. Pizzol:** Methodology, Conceptualization, Writing – review & editing, Resources, Supervision, Funding acquisition. **A. Tinello:** Methodology, Formal analysis, Investigation, Conceptualization, Validation. **P. Scanferla:** Resources, Supervision, Funding acquisition, Project administration, Writing – review & editing. **A. Zabeo:** Resources, Data curation, Supervision, Writing – review & editing. **S. Breda:** Resources, Writing – review & editing. **A. Marcomini:** Resources, Supervision, Funding acquisition, Writing – review & editing. **S.A. Frisario:** Supervision, Writing – review & editing. **L. Zaninetta:** Supervision, Writing – review & editing. **G. Bonfedi:** Supervision, Writing – review & editing. **F. Villani:** Supervision, Writing – review & editing. **E. Semenzin:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgement

The authors declare no conflicts of interest. Although Eni Rewind S.p.A. contributed to fund the research, the authors declare that the company did not interfere in any activity of the research.

The work was entirely done by the listed authors, with no assistance of other individuals or organization.

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