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Review

Sustainable Production of Rare Earth Elements from Mine Waste and Geoethics

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Abstract: The vulnerability of the rare earth element (REE) supply in a global context of increasing demands entails important economic and political issues, and has encouraged several countries to develop their own REE production projects. This study comparatively evaluated the production of REEs from primary and secondary resources in terms of their sustainability and contribution to the achievement of the Geoethics concept as responsibility towards oneself, colleagues, society, and the Earth system. Twelve categories of potential environmental and social impacts were selected: human health toxicity, global warming or climate change, terrestrial and aquatic eutrophication, acidification potential, particulate matter, resource depletion, water consumption, fresh water ecotoxicity, ionizing radiation, fossil fuel consumption, and ozone depletion. The results showed that the environmental impact of REE production from secondary sources is much lower relative to primary sources. A comparison of conventional and non-conventional REE resources showed that significant impact categories were related to particulate matter formation, abiotic resource depletion, and fossil fuel depletion, which could result from avoiding the tailings disposal before reuse. Based on these findings, governments and stakeholders should be encouraged to increase the recycling of secondary REE sources with Geoethics in mind, in order to balance the high demand of REEs while minimizing the overexploitation of non-renewable resources.

Keywords: rare earth elements; Geoethics; mine waste

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1. Introduction

The potential vulnerability of the rare earth element (REE) supply in a global context of increasing demands in recent years [1] entails important economic and political issues, and has encouraged several countries—in addition to China (the largest REE producer)—to develop their own production projects [2,3]. For example, Canada has more than 50 projects in development, even though no REE mining sites are currently active [3]. This expansion of the production and use of REEs could increase human exposure and the associated adverse risks [4]. Traditionally, mining is well known to be responsible for adverse effects causing environmental damage, health problems, forced population displacement, increased social inequality and corruption, etc. [5]. In addition, REE production generates important social and environmental impacts because of the use of strong and corrosive chemicals, and because of the generation of radioactive co-products such as U and Th [6]. However, if it is responsibly managed, the mining industry can bring positive social and economic benefits such as job creation, investment, innovation, and infrastructure improvement [5]. In the context of the circular economy and sustainability, mining waste represents a potential source for REE extraction. This approach aims to transfer the mining operations from an "open cycle" to a "closed cycle", in which mining waste is re-used, recycled, recovered, or re-processed rather than being discharged, landfilled, or disposed of [7]. In order to consider the social and environmental perspectives of a mining project and make an informed decision, Geoethics can be the key to properly integrate all of the factors. The Geoethics concept refers to the responsibility towards oneself, colleagues, society, and the Earth system [8]. However, few documented studies have focused on these methods and processes.

The main objective of this study was to comparatively evaluate the production of REEs from primary and secondary resources in terms of their sustainability and contribution to the achievement of the Geoethics concept.

1.1. Conventional or Primary Resources for REE Extraction

The conventional extraction of REEs exploits the mining of REE-bearing minerals. REEs are found in many minerals, but few can be exploited economically [9]. Bastnäsite deposits are the largest economic REE resource and are found mainly in China and the United States of America [10]. Bastnäsite is an REE fluorocarbonate mineral ($REECO_3F$), mostly containing light REEs. There are many different methods for processing bastnäsite, but they commonly include fluoride and carbon dioxide (CO_2) removal steps, such as calcination, acid leaching, or alkali treatment [11]. During the removal process, fluoride and CO_2 are released from the ore as a gaseous phase or an aqueous phase (e.g., hydrofluoric acid, alkali fluoride). Then, the remaining REE compounds (REE oxide, REE hydroxide, etc.) are leached in an acidic solution and separated into each element by solvent extraction [12]. Overall, the separation of REE oxides is the most polluting process [13,14].

Other minerals used for commercial production are monazite, xenotime, and ion-adsorbed clays [9]. Monazite and xenotime are REE phosphate ($REEPO_4$) and yttrium phosphate (YPO_4) minerals, respectively. As they are both phosphates, similar extraction processes can be applied. The minerals are first decomposed by acid or alkali treatment (e.g., H_2SO_4 baking or NaOH digestion). The decomposed products can then be leached in water or an acidic solution to extract the REEs. During the treatment of phosphate minerals, specifically monazite, radioactive elements (U and Th) can also be extracted, as monazite ores generally contain these elements [15]. Extracting REEs from ion-adsorbed clays is somewhat easier, as REEs are physically adsorbed onto clay surfaces. Adopting the concept of ion-exchange, REEs are recovered from ion-adsorbed clays by in-situ leaching while injecting an ammonium sulfate solution through an injecting well [16]. However, the continuous solution injection can cause serious problems, including landslides due to the change in pore structure [17].

1.2. Non-Conventional or Secondary Resources for REE Extraction

Secondary sources of REEs include their recovery from waste, including electronic or electrical waste, mine tailings, contaminated residuals from mine drainage treatment, red mud, and phosphogypsum [10,18–23]. Phosphogypsum (PG), originating from the digestion of phosphate rocks, contains up to 0.40% REEs. Even though this concentration is low, the recovery of REEs from PG could be a considerable secondary source due to the large amount of PG produced globally [19]. The REEs in PG can be recovered by inorganic acid leaching using HCl, HNO_3, and H_2SO_4. Although H_2SO_4 is preferred in most hydrometallurgical processes, it is not applicable for PG processing, as sulfate ions cause calcium sulfate precipitation when reacting with calcium from the PG, and REEs can be co-precipitated [24]. HCl is the most favorable, as it gives the highest leaching efficiency [25].

Uranium-based mining residues also contain REEs, in a proportion of $0.26 \pm 0.20\%$ in Canadian uranium deposits [26]. Acid mine drainage (AMD), generated by the natural oxidation of sulfide minerals, is rich in cationic metals, including REEs. REEs in AMD can be recovered through staged precipitation, but this generally requires high chemical consumption due to the low REE content in AMD [27]. The removal of REEs from contaminated waters derived from mine activities through sorption or precipitation processes could be a potential secondary source of these elements [23]. Tailings and waste materials, such as those from fluorite mines, could also be a potential secondary source of REEs, but further research is needed [28].

Another common REE source is coal ash. Indeed, the REE concentrations in coal fly ash range from 250 to 480 ppm [29]. If the fly ash is separated based on its particle size or material density, the concentration can be increased up to 570 ppm (for less than 38-µm diameters) or 530 ppm (for hydrocyclone overflow). In addition, it has been reported that the REE concentrations in coal fly ash can reach 754.5 ppm, and this concentration can be increased up to 1052 ppm after ash desilication [30].

1.3. Mining: Sustainability, Circular Economy, and Geoethics

In general, the sustainability of REE production is focused on reducing the environmental and social impacts related to REE mining. In order to foster and achieve sustainability, mining activities must be responsibly performed using the best practices. Responsible mining is defined as a: *commitment to managing the economic, social and environmental challenges related to mineral resources development and building a system capable of ensuring/promoting responsible extraction of minerals while developing a proper alignment of the corresponding benefits at local, regional, national and global scales* [31].

Responsible mining is thoroughly related to the principles and ethics of sustainable development during the mine's life cycle [31]. This concept includes several steps, from exploration, mining, beneficiation, refining, by-product/waste management, and mine closure, to mine-site reclamation [31]. For stakeholders directly affected by the mining activities, responsible mining attempts to create trusting and transparent relationships. Moreover, it aims to enhance the creation of sustainable benefits for local communities and government authorities [32]. Responsible mining attempts to reduce environmental impacts related to water, biodiversity, and land, and attempts to protect human health [31,32].

A close relationship exists between sustainability and Geoethics. According to the Cape Town Statement on Geoethics, the term Geoethics deals with "*the ethical, social and cultural implications of geosciences knowledge, education, research, practice and communication, and with the social role and responsibility of geoscientists in conducting their activities*" [33]. Consistently, Geoethics is a framework of global ethical assumptions that interact with the different aspects of science [34]. Based on these interactions, the purposes of Geoethics can include the development of sustainable benefits for communities and the protection of local and global environments, with the aim to maintain a prosperous development for future generations [33]. In the same context of Geoethics, the exploitation of georesources during mining involves significant social and environmental risks [35]. Therefore, responsible solutions that integrate ethical and social impacts need to be considered in order to provide a healthy and safe life with respect for the geo-ecosystems [36].

Historically, conventional mining activities that excluded Geoethical considerations during their life cycle had a negative impact on the main planetary spheres (the lithosphere, atmosphere, hydrosphere, and biosphere) and their components (relief, subsoil, troposphere, surface waters, ground waters, vegetation, and animals) [34]. Generally, Geoethics has four domains and areas of application, including the responsibility towards oneself (i.e., the individual domain), the responsibility towards colleagues (i.e., the inter-personal domain), the responsibility towards society (i.e., the societal domain), and finally the responsibility towards the Earth system (i.e., the environmental domain) [37–39] (Figure 1).

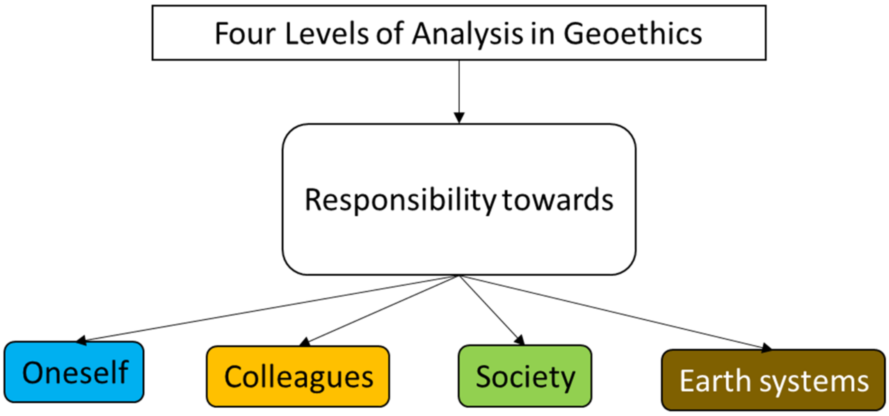

Figure 1. Levels of responsibility in the geoethical framework.

These domains represent an interesting framework for the development of a responsible approach while increasing the awareness of individual and social responsibilities towards the work environment, society, and the Earth [39]. Moreover, while evaluating mining activities, geoethical thinking considers some key points, including the sustainable use of georesources, georisks, the reduction and prevention of pollution, the management of the land, the socio-environmental impacts of supplying energy, the assessment of the impacts of pollution on health, the prevention of climate change, and the protection of geodiversity [36].

From an environmental point of view, the reprocessing of REEs from already-stockpiled mine waste is more sustainable than the extraction of non-renewable virgin ore from the Earth's crust; this approach will limit the depletion of finite resources, enhance biodiversity, minimize the generation of radioactive elements and dust, decrease water and soil contamination as well as energy consumption, and reduce CO_2 emission and landfilling [40]. In addition, the reprocessing of mine tailings could help to mitigate environmental problems related to tailings disposal, AMD generation, the release of heavy metal contamination, and dam failures [41]. In term of social impacts, the reprocessing of REEs from mine waste could reduce the harmful effects on both human and aquatic health by mitigating the production of radioactive/carcinogenic elements and minimizing noise and dust emissions [40,42]. From an economic point of view, with the increasing REE prices and supply shortages, the exploitation of secondary resources could be beneficial to enhance economic growth and resource diversification. The cost of metal extraction from mine waste is often more economically attractive than mining a primary ore body, as this waste (i.e., tailings) has already been processed [43]. However, because of several challenges of REE reprocessing, such as the limitations of the extraction technologies and the variation of REE concentrations in the mine waste, the repurposing of mine waste could have limited economic benefits [40]. Overall, while reprocessing mine waste for REE recovery, the REE operation costs, environmental and global ecological footprints of the process, impacts on public health, and social benefits must be carefully considered. Hence, in order to protect and improve environmental performance, and to ensure the safety of the storage facility, the reprocessing of waste must be carried out with the best available techniques and standards [44]. Finally, while establishing the concepts of responsible, sustainable, or ethical mining, several protocols must be considered in order to limit unacceptable environmental and social impacts caused when mining activities are not managed according to the best practice standards [45].

2. Materials and Method

2.1. Geoethics of REE Extraction from Primary vs. Secondary Sources

The quantification of social and environmental impacts using the life cycle impact assessment (LCIA) method was performed in order to make a comparison between primary and secondary resources for REE extraction. Moreover, it could be used to determine whether a mining project responds to two of the four levels of responsibility in the Geoethics concept: the responsibility towards society and the Earth systems.

In order to apply the LCIA method, the literature regarding REE extraction impacts was extensively reviewed, serving as the data collection. Only a few LCIA studies on the production of REEs from secondary or non-alternative resources have been published to date. According to the authors' best knowledge, the existing literature dealing with primary REE sources and LCIA is mainly concentrated on mineral deposits in Bayan Obo and Southern Provinces (China), Mountain Pass (USA), and Mount Weld (Australia). In total, 20 articles dealing with LCIA for the mining, beneficiation, and refining (with potential separation in some cases) of rare earth oxides (REO) and REEs were selected. Depending on the deposit type (e.g., alkaline, carbonatites, laterite, clays), location (China, USA, Australia, etc.), mineralogy (e.g., bastnäsite, monazite, and xenotime), and ore grades, the mining/extraction step for REEs could be performed through open-pit mines, underground mining, and heap, dump, and in-situ leaching [46]. In general, the beneficiation stage—mainly related to REE-bearing mineral concentration, purification, and separation from the gangue/non-economic rocks—involved crushing, grinding, separation, flotation, thermal treatment, filtering, and washing, etc. [46]. During the refining stage, concentrated REEs—obtained from the beneficiation stage—underwent several sub-steps, including caustic/acid leaching, roasting, co-product separation, solvent extraction, and precipitation, etc. [46]. Overall, 14 papers were rigorously studied using LCIA for REE extraction from primary deposits, while six additional papers focused on REE extraction from waste materials (e.g., tailings, electronic, magnet and fluorescent powders). Then, the key parameters—including the ecosystem, human health, and resource impacts— were carefully identified and used for comparison purposes (Figure 2).

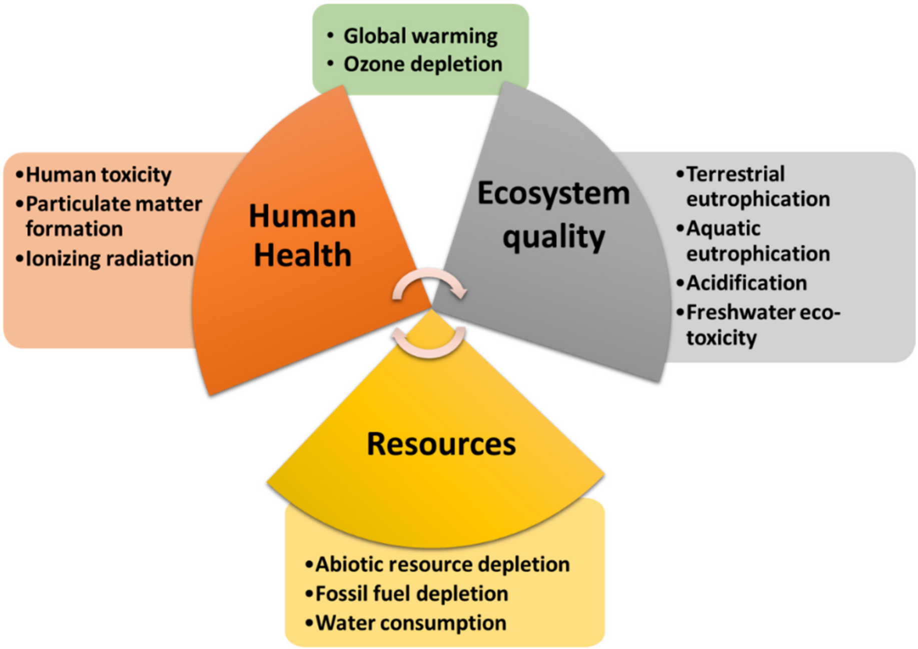

Figure 2. Ecosystem, human health, and resource impacts in the LCIA.

There are several limitations when comparing results among studies of LCIA for REE extraction: (1) differences in system boundaries (e.g., inputs, outputs, production routes), (2) source and quality of life cycle inventory data gaps (e.g., Ecoinvent 3), (3) the geographic region under consideration (e.g., China, the USA, Australia), (4) the variability of the project stage (e.g., prefeasibility, cradle-to-gate production, cradle-to-grave production), (5) life cycle analysis software (e.g., GaBi, SimaPro 8), (6) the selection of LCIA methods (e.g., CML, ReCiPe, ILCD, CED, IPCC, and TRACI), and (7) the allocation technique (e.g., economic valued-based allocation vs mass-based allocation) [46–48]. Despite the existing differences, results from LCIA are still useful for the communication of impacts to non-specialists [47].

2.2. Categories of Potential Environmental and Social Impacts

Based on the available data, 12 categories (Table 1) of potential environmental and social impacts were selected: human health toxicity (cancer effects), global warming or climate change, eutrophication (terrestrial and fresh water), acidification potential, particulate matter, resource (abiotic and fossil fuel) depletion, water consumption, fresh water ecotoxicity, ionizing radiation, and ozone depletion [49–55]. More detailed information about each parameter is provided in the following sections.

Table 1. Categories of potential environmental and social impacts used in LCIA.

Impact Category	Unit
Acidification	kg SO_2 eq.
Freshwater eutrophication	kg $PO_4{}^{3-}$ eq.
Terrestrial eutrophication	kg N eq.
Global warming potential or climate change	kg CO_2 eq.
Particulate matter formation	kg $PM_{2.5}$ eq.
Water consumption	kg/kg eq.
Abiotic resource depletion	kg Sb eq.
Fossil fuel depletion	MJ
Ozone depletion	kg CFC-11 eq.
Ionizing radiation	kBq ^{235}U eq.
Freshwater ecotoxicity	kg 1,4-DCB eq. or CTUe
Human toxicity	kg 1,4-DCB eq. or CTUh

2.2.1. Acidification (kg SO_2 Equivalents)

Acidification results from the deposition of nitrous and sulfur oxides, sulfuric acid, and ammonia on the land (terrestrial) or in water (aquatic). It decreases the pH and, therefore, increases the potential release of toxic elements from soils and deposits, etc. Acidifying substances are often air emissions, which could be wet-deposited as acid rain, fog, or snow, or dry-deposited as dust or smoke particulates in the soil or water [50–54].

2.2.2. Freshwater (kg $PO_4{}^{3-}$ Equivalents) and Terrestrial Eutrophication (kg N Equivalents)

Eutrophication is the enrichment of an ecosystem with nutrients that accelerate biological productivity and therefore result in an undesirable accumulation of biomass. Terrestrial eutrophication is caused by nitrogen released to the soil, and is quantified based on the increased susceptibility of plants to diseases. Aquatic eutrophication is caused by phosphate released to the water, and is quantified based on the excessive growth of algae, which decreases sunlight infiltration and increases oxygen depletion [49–55].

2.2.3. Global Warming Potential or Climate Change (kg CO_2 Equivalents)

Climate change consists of an increase of greenhouse gas (i.e., carbon dioxide, methane, and nitrous oxide, etc.) emissions to the air. This increase affects the absorption of infrared radiation in the atmosphere, which therefore negatively influences human health and material welfare, and contributes to higher global average temperatures [49,51,52,54,55].

2.2.4. Particulate Matter Formation (kg $PM_{2.5}$ Equivalents)

Particulate matter formation is based on the collection and emission of small particles in the air that are harmful for human health and could cause negative effects, including respiratory illness and death [49,50,53–55].

2.2.5. Water Consumption (kg/kg Equivalents)

Water is one of humanity's most valuable resources. Water consumption corresponds to the calculation of the amount of water used/consumed or polluted (degraded) for the creation of a product [50–53].

2.2.6. Abiotic Resource Depletion (kg Sb Equivalents)

Abiotic resource depletion refers to the depletion of non-living resources (i.e., minerals, clay, peat, etc.) based on the concentration of their reserves [50,53–55].

2.2.7. Fossil Fuel Depletion (MJ)

Fossil fuel depletion quantifies the depletion of resources containing hydrocarbons (i.e., methane, gasoline, coal, etc.).

2.2.8. Ozone Depletion (kg CFC-11 Equivalents)

Ozone depletion quantifies the impact of the decrease in the ozone concentration in the stratosphere. Indeed, because ozone molecules absorb large quantities of ultraviolet radiation, a reduction in their concentration will have a serious effect on life at the surface of the Earth, including damage to plants, animals, and humans [50,54].

2.2.9. Ionizing Radiation (kBq ^{235}U Equivalents)

Ionizing radiation is based on the emission of radionuclides to the air and water from nuclear electricity generation (e.g., U mining and milling), coal, natural gas and oil combustion, geothermal energy extraction, and nuclear spent-fuel reprocessing, etc. [50,52,53].

2.2.10. Freshwater Ecotoxicity (kg 1,4-DCB Equivalents or CTUe)

Freshwater ecotoxicity quantifies the impact on fresh water of the emissions of toxic substances to ecosystems, including the air, water, and soil [50–52].

2.2.11. Human Toxicity (kg 1,4-DCB Equivalents or CTUh)

The human toxicity impact evaluates the exposure, fate, and effects of toxic substances on the human environment. It measures the degree of the production of illness or damage to an exposed human [49,53,55].

3. Results

In order to compare the different sources of REEs using the LCIA method, three categories were defined: (1) primary sources from bastnäsite, monazite, synchysite, and eudialyte (B/M/S/E) minerals; (2) primary sources from ion-adsorption clays (IAC); and (3) secondary materials (SM) from tailings, electronics, magnets and fluorescent powders. The results are shown in Figure 3, while the detailed data for each category are presented in Tables A1–A4 of Appendix A.

The median value for the acidification potential was similar for both primary sources (B/M/S/E: 2.27×10^{-1} kg SO_2 eq., $n = 18$; IAC: 2.32×10^{-1} kg SO_2 eq., $n = 18$). This higher acidification potential for IAC compared to B/M/S/E followed the same trend as the results found by Arshi et al. (2018) [56], which suggested that the ammonium and sulfate emissions to water in the IAC leaching process were responsible for the acidification. The overall difference between the primary sources was low; however, it can be noted that the acidification potential was more than 25 times lower for SM (8.73×10^{-3} kg SO_2 eq., $n = 7$) compared to the primary sources, even though the highest acidification potential recorded in this review was from a secondary source. The highest value was associated with the production of Sc from the tailings from the Bayan Obo Mine, with a value of $1.58 \times 10^{+1}$ kg SO_2 eq. [48]. According to the authors, Sc production has a greater environmental impact than other REOs due to the lower concentration of Sc and the difficult extraction/separation of this specific metal compared to other REEs. Except for this maximum, the other acidification potential data from the SM were all lower than the median values of the primary sources, with the lowest values being calculated from recycling processes of materials such as magnets and fluorescent powders [57].

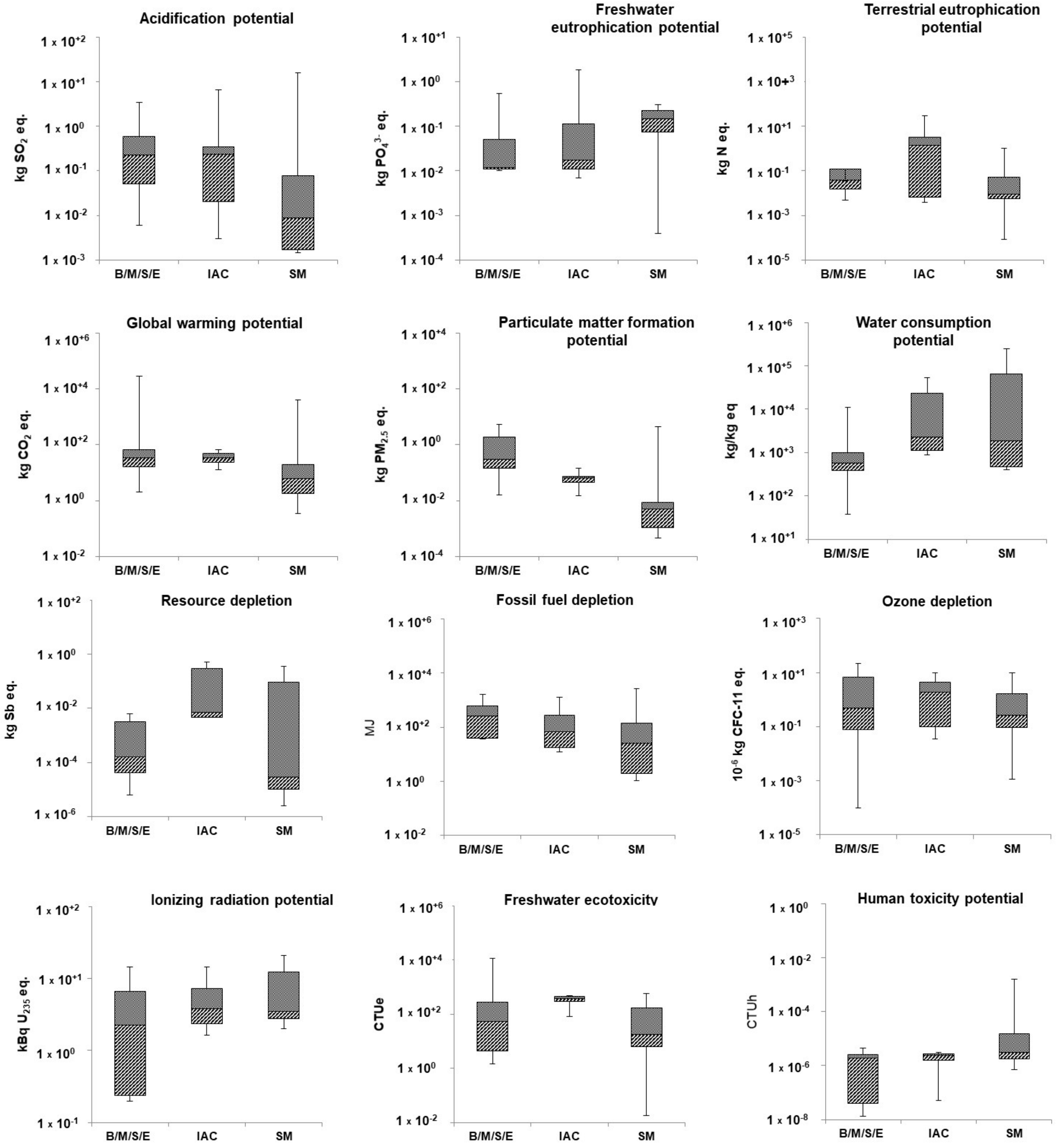

Figure 3. Comparison of the different impacts between primary (B/M/S/E and IAC) and secondary source materials (SM) for REE production.

On the other hand, LCA analyses indicated that the SM could lead to greater freshwater eutrophication compared to the primary sources. However, the small amount of data collected (*n* = 2 for SM compared to *n* = 19 for B/M/S/E and IAC combined) needs to be considered. The opposite trend was found for the terrestrial eutrophication potential, where the median value for SM (3.24×10^{-3} kg N eq., $n = 6$) was lower than both primary sources. The eutrophication potential (both freshwater and terrestrial) was higher for IAC compared to B/M/S/E, and can largely be explained by the in-situ emission of ammonium [58].

The global warming potential was similar for both primary sources (B/M/S/E and IAC minerals, with median values of $3.30 \times 10^{+1}$, $n = 23$, and $3.43 \times 10^{+1}$ kg CO_2 eq., $n = 10$, respectively), and about 5.5 times higher than the secondary sources of REEs (6.0 kg CO_2 eq., $n = 9$). For B/M/S/E, this higher potential environmental footprint could be explained by the diesel generators used for the REE extraction [56]. This use of fuel for the extraction of REEs from B/M/S/E minerals can be observed in Figure 3 with the fossil fuel depletion potential, for which the median value was 3.7 times higher for primary REE sources from B/M/S/E minerals ($2.53 \times 10^{+2}$ MJ) compared to IAC ($6.9 \times 10^{+1}$ MJ), and 10 times higher than SM ($2.49 \times 10^{+1}$ MJ). However, concerning the global warming potential, there was a large gap among the different secondary materials analyzed: the REEs extracted from tailings showed a mean value of $9.87 \times 10^{+2}$ kg CO_2 eq. [48,59,60], whereas the REEs extracted from secondary materials such as electronics, magnets, and fluorescent powders had a mean value of $1.2 \times 10^{+1}$ kg CO_2 eq. in the selected articles [57,61,62]. According to Wang et al. (2020), the processing of the tailings requires a lot of energy and materials [48]. Concerning recycled materials, the recovery of Eu from recycled fluorescent powders could decrease the carbon footprint by up to 200 times compared to the primary production of this metal from conventional mining [57]. However, according to Wall et al. (2017), the most significant source of greenhouse gases came from the chemical reagents used to dissolve and separate individual REEs, because the production of these reactants can require the use of fossil fuels [63]. The refining stages, more than the other steps, had the most significant impact on the environment [46]. For SM, the use of organic solvents was also a cause of the high resource depletion potential. There was also a significant difference between the production of light and medium/heavy REEs, with a global warming and an energy consumption potential about 25 times higher (for both categories) in the production of the heavier REEs relative to the lighter elements [64].

The particulate matter formation potential was about 4.6 times higher for B/M/S/E (median value = 3.00×10^{-1} kg $PM_{2.5}$ eq., $n = 12$) compared to IAC (6.5×10^{-2} kg $PM_{2.5}$ eq., $n = 8$), and 50 times higher than SM (6×10^{-3} kg $PM_{2.5}$ eq., $n = 6$). This could be explained by the open-pit mining and diesel generators used for REE extraction from B/M/S/E minerals [56]. An opposite trend was found for the water consumption potential, with the lowest values collected from REEs extracted from B/M/S/E minerals, which had a median value about 4 times lower than IAC and SM.

The highest freshwater ecotoxicity potential was calculated from IAC deposits (median value = $3.67 \times 10^{+2}$ CTUe, $n = 6$), and was about 7 times higher than that calculated for B/M/S/E materials ($5.25 \times 10^{+1}$ CTUe, $n = 9$) and 10 times higher than that for SM ($3.6 \times 10^{+1}$ CTUe, $n = 7$). According to Bailey et al. (2020), REE extraction from IAC produces large quantities of metal-rich in situ wastewater compared to other sources, which can cause a higher aquatic toxicity [65]. A similar trend was observed for the human toxicity potential.

4. Discussion

The goal of the LCA studies mentioned here was to identify environmental issues associated with REE recovery, and thereby to point out geoethical responsibilities towards the Earth system. Throughout the comparative analysis, it was found that the environmental impacts of REE production from SM were much lower than those for the direct production from the primary raw ores. The comparison of variants for conventional and non-conventional REE resources showed that significant impact categories were related to particulate matter formation, abiotic resource depletion, and fossil fuel depletion, which could result from avoiding the tailings disposal before reuse. The fossil depletion category indicator depends on the type of the fuel used during the transportation or exploitation processes (natural gas, coal, crude oil, etc.). Moreover, tailings leftover after REE reprocessing from secondary materials were disposed of or landfilled, which can entail negative environmental impacts related to freshwater ecotoxicity and human toxicity. In general, during the exploitation of REEs from primary sources, substantial amounts of external energy and materials were used. Furthermore, harmful effluents were released to the environment. In terms of energy consumption, this input could be largely reduced. For instance, it is well known that grinding is an energy-consuming process. Hence, as tailings have been ground already, the consumption of electricity could be substantially decreased. Likewise, lower energy consumption induces a lower global warming potential. Indeed, high values in the global warming category were mainly caused by CO_2 emissions from the production of electricity. Moreover, the reuse of SM largely decreased the acidification potential, and was thus much more environmentally friendly, with lower environmental impacts than extracting REEs from bastnäsite/monazite or clays. Even though the REE recovery from SM generated positive impacts in several categories, high freshwater eutrophication—resulting from the release of phosphate to the water—and ionizing radiation potentials could be encountered during the processing. In order to minimize these negative impacts, the reuse of other SM including fly ash, coal ash, and bauxite (red mud) could be considered, as they were demonstrated to be promising materials for REE extraction [66].

In order to balance the high demand of REEs while minimizing the overexploitation of non-renewable resources, it is recommended that governments and stakeholders increase SM recycling as a step towards a geoethical approach to these issues. It was obvious from this study that, in general, the REE production from SM has lower environmental impacts; thus, SM can be considered as a sustainable raw material. The recovery of REEs can reduce the amount of the primary resources which need to be extracted, thereby enhancing the geoethical behavior of the mining industry. Indeed, the environmental impact of REE production from SM is much lower relative to primary sources. The comparison of conventional and non-conventional REE resources indicated that important impact categories were related to particulate matter formation and resource depletion (e.g., abiotic, fossil fuel) resulting from the mining excavation and tailings disposal. The recovery of REEs from waste could be considered as a remediation method to avoid waste landfilling while minimizing the overexploitation of non-renewable resources. However, in order to reduce the negative impacts of SM processing, some assumptions must be considered: the input material for REE extraction should be obtained directly from the tailings production facility in order to avoid unnecessary disposal and transportation, and green environmental technologies (materials and equipment) should be investigated and deeply studied. Overall, increasing the recycling of secondary REE sources would contribute not only to the achievement of the Geoethics concept but also to the balance of the increasing demand for REEs.

5. Conclusion

From a geoethical point of view, there is a need to consider the responsibility towards society and the Earth system when exploiting georesources. From a human health perspective, the extraction of REEs from secondary materials would be less harmful, considering the lower global warming, particulate matter formation, and toxicity potentials when compared to both primary sources of REEs analyzed in this study (B/M/S/E and IAC). Furthermore, secondary sources of REEs would have a lower environmental impact on the ecosystem quality, based on the lower acidification, terrestrial eutrophication, and fossil fuel depletion potentials than both primary sources of REEs (B/M/S/E and IAC). However, the extraction of REEs from SM would have higher freshwater eutrophication, water consumption, and ionizing radiation potentials than the primary sources. Therefore, to be consistent with the concept of Geoethics, further research is still needed in order to reduce the environmental and societal impacts of REE production from secondary materials.

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Appendix A

Table A1. LCIA of REE primary production from bastnäsite and monazite minerals.

Mine Site		**Bayan Obo 1**						**Bear Lodge**
Reference		[9]	[67]	[68]	[69]	[56]	[70]	[71]
Country		China						USA
Deposit		Bastnäsite and Monazite						
1kg REO/REE to Be Extracted		LREO-HREO	REO	LREO-HREO	REO	Nd_2O_3	REO	REO
Acidification potential (kg SO_2 eq.)		-	1.4–2.2 × 10^{-1}	1.85–1.92 *	2.81–33.89 × 10^{-1}	7.4 × 10^{-1}	2.4 × 10^{-1}	6 × 10^{-3}
Freshwater ecotoxicity potential	(CTUe)	-	-	3.07–5.25× 10^{+1}	-	2.20–2.78 × 10^{+2}	-	1.45
	(kg 1,4-DCB eq.)	-	2.7–3.5	-	2.39–20.3 × 10^{-1}	-	9.5 × 10^{-1}	-
Freshwater eutrophication potential (kg P eq.)		-	-	-	1.2–55.0 × 10^{-2}	1.2 × 10^{-2}	8 × 10^{-2}	-
Terrestrial eutrophication potential (kg N eq.)		-	4–6 × 10^{-2}	1.8–2.7 × 10^{-1}	-	1.4 × 10^{-1}	-	1.3 × 10^{-2}
Global warming potential (kg CO_2 eq.)		3.03–3.45 × 10^{+1}	1.2–1.6 × 10^{+1}	2.298–3.53× 10^{+2}	3.46–6.34 × 10^{+1}	8.93 × 10^{+1}	3.10 × 10^{+2}	1.21 × 10^{+1}
Human toxicity potential	(CTUh)	-	-	1.9–3.1 × 10^{-6}	-	4.42 × 10^{-6}	-	1.3 × 10^{-8}
	(kg 1,4-DCB eq.)	-	3.6–32.0 × 10^{+1}	-	4.3–850	-	2.0 × 10^{+1}	-
Particulate matter formation potential (kg PM2.5 eq.)		-	-	1.6–1.8 × 10^{-1}	-	4.7 × 10^{-1}	2.5	1.6 × 10^{-2}
Water consumption potential (kg/kg eq.)		3.76–3.81 × 10^{+1}	-	-	4.17–9.00 × 10^{+2}	7.43× 10^{+2}	-	-
Resource depletion (kg Sb eq.)		-	-	-	0.5–1.6 × 10^{-4}	6.14× 10^{-3}	-	-
Energy consumption (MJ)		1.69–1.80 × 10^{+2}	1.74–2.32 × 10^{+2}	3.15–5.79 × 10^{+2}	4.93–9.85 × 10^{+2}	-	-	-
Fossil fuel depletion (MJ)		3.65–3.93 × 10^{+1}	-	-	4.93–9.85 × 10^{+2}	1.47 × 10^{+3}	2.93 × 10^{+2} **	4.05 × 10^{+1}
Ozone depletion potential (kg CFC-11 eq.) × 10^{-6}		-	2.7	3.8–19.7	0.77–1.3 × 10^{-1}	1.75 × 10^{+1}	1.2	2.4 × 10^{-3}
Ionizing radiation potential (kBq U_{235} eq.)		-	-	-	-	6.56	2.9	-

* Calculated from H^+ mol eq.; **calculated from kg oil eq. Abbreviations: REO, Rare Earth Oxide; LREO, Light Rare Earth Oxide; HREO, Heavy Rare Earth Oxide.

Table A2. LCA of REE primary production from bastnäsite, monazite, synchysite, and eudialyte minerals.

Mine Site		**Mine X**	**Mount Weld 1**	**Mount Weld 2**	**Bayan Obo 1**	**Bayan Obo 2**	**Sichuan**	**Mountain Pass**	**Songwe Hill**	**Norra Kärr**
Reference		[72]	[70]	[64]	[65]	[65]	[69]	[70]	[47]	[73]
Country		Australia			China			USA	Malawi	Sweden
Deposit		Monazite				Bastnäsite			Synchysite	Eudialyte
1kg REO/REE to Be Extracted		REE	REO	REO	REO	REO	REO	REO	REO	Dy
Acidification potential (kg SO_2 eq)		-	3×10^{-2}	-	2×10^{-2} *	1.5×10^{-2} *	$1.38–2.34 \times 10^{-1}$	5×10^{-2}	$5.4–63.75 \times 10^{-2}$	4.5×10^{-1}
Freshwater ecotoxicity potential	(CTUe)	-	-	-	$6.11 \times 10^{+2}$	$1.17 \times 10^{+4}$	-	-	1.50–4.32	-
	kg 1,4-DCB eq.	4.6×10^{-3}	1×10^{-1}	-	-	-	$1.28–2.12 \times 10^{-1}$	1.2×10^{-1}	-	2
Freshwater eutrophication potential (kg P eq.)		-	$<1 \times 10^{-2}$	-	2.0×10^{-2}	1.2×10^{-2}	$1–12 \times 10^{-2}$	$<1 \times 10^{-3}$	-	1.5×10^{-2}
Terrestrial eutrophication potential (kg N eq.)			-	-	8.1×10^{-3}	3.6×10^{-2}	-	-	$5–20 \times 10^{-3}$	-
Global warming potential (kg CO_2 eq.)		$6.54 \times 10^{+1}$	2	$1.82–2.75 \times 10^{+1}$	$3.30 \times 10^{+1}$	$3.81 \times 10^{+1}$	$1.63–2.83 \times 10^{+1}$	7	$1.703–8.726 \times 10^{+1}$	$1.45 \times 10^{+2}$
Human toxicity potential	(CTUh)	-	-	-	2.59×10^{-6}	2.52×10^{-6}	-	-	$1.1–6.7 \times 10^{-8}$	-
	kg 1,4-DCB eq.	1.53	$1.5 \times 10^{+1}$	-	-	-	4.4–7.6	$2.0 \times 10^{+1}$	-	$3.5 \times 10^{+1}$
Particulate matter formation potential (kg PM2.5 eq.)		-	2×10^{-1}	-	9.1×10^{-2}	6.1×10^{-2}	-	4×10^{-1}	5.16–5.21	1.6 ****
Water consumption potential (kg/kg eq.)		$1.117 \times 10^{+1}$	-	1.31–1.81	$5.22 \times 10^{+2}$	$5.30 \times 10^{+2}$	$2.85–6.29 \times 10^{+2}$	-	-	-
Resource depletion (kg Sb eq.)		-	-	-	2.1	4.5×10^{-3}	$0.64–3.2 \times 10^{-5}$	-	-	-
Energy consumption (MJ)		$9.17 \times 10^{+2}$	-	$3.02–4.08 \times 10^{+2}$	-	-	$2.12–3.98 \times 10^{+2}$	-	-	-
Fossil fuel depletion (MJ)		-	$3.35 \times 10^{+1}$ **	-	-	-	$2.12–3.98 \times 10^{+2}$	$1.59 \times 10^{+2}$ **	-	$1.675 \times 10^{+3}$**
Ozone depletion potential (kg CFC-11 eq.) $\times 10^{-6}$		-	2×10^{-1}	-	9.53	6.75	$7.3–9.4 \times 10^{-2}$	5×10^{-1}	$1.0–1.6 \times 10^{-4}$	$2.1 \times 10^{+1}$
Ionizing radiation potential (kBq U_{235} eq.)		-	2×10^{-1}	0.24–2.02 ***	6.76	2.27	-	2×10^{-1}	-	$\times 10^{+1}$

* Calculated from H^+ mol eq.; ** calculated from kg oil eq.; *** hours/life; **** kg PM_{10} eq. Abbreviations: REO, Rare Earth Oxide; LREO, Light Rare Earth Oxide; HREO, Heavy Rare Earth Oxide.

Table A3. LCA of REE primary production from ion-adsorption clays.

Mine Site		**Southern Provinces 1**	**Southern Provinces 2**	**Southern Provinces 3**	**Southern Provinces 4**	**Southern Provinces 5**	**Southern Provinces 6**
Reference		[74]	[69]	[73]	[65]	[75]	[56]
Country		China					
Deposit		Ion Adsorption Clays					
1kg REO/REE to Be Extracted		REO	REO	REO	REO	HREO	Nd_2O_3
Acidification potential (kg SO_2 eq.)		3-6 × 10^{-3} *	2.94–7.29 × 10^{-1}	6.5–32 × 10^{-2}	6 × 10^{-3} *	1.7–3.5 × 10^{-1}	6.46
Freshwater ecotoxicity potential	(CTUe)	2.80–4.51 × 10^{+2}	-	8.0–49.1 × 10^{+1}	4.28 × 10^{+2}	2.54–3.61 × 10^{-3}	3.05 × 10^{+2}
	(kg 1,4-DCB eq.)	-	1.94–5.21 × 10^{-1}	-	-	-	-
Freshwater eutrophication potential (kg P eq.)		1.11–1.78 × 10^{-2}	3.91–18.22 × 10^{-1}	-	1.7 × 10^{-2}	0.7–1.1 × 10^{-2}	1.9 × 10^{-2}
Terrestrial eutrophication potential (kg N eq.)		2.8–4.6 × 10^{-1}	-	3.25–29.4	4.6 × 10^{-1}	-	2.7
Global warming potential (kg CO_2 eq.)		2.09–3.55 × 10^{+1}	3.06–6.72 × 10^{+1}	1.3–5.2 × 10^{+1}	4.05 × 10^{+1}	1.88–3.31 × 10^{+1}	6.36 × 10^{+1}
Human toxicity potential	(CTUh)	1.4–2.2 × 10^{-6}	-	0.005–0.3 × 10^{-5}	2.65 × 10^{-6}	-	2.67 × 10^{-6}
	(kg 1,4-DCB eq.)	-	1.7–5.3	-	-	-	-
Particulate matter formation potential (kg PM2.5 eq.)		3.2–6.0 × 10^{-2}	-	1.5–7 × 10^{-2}	4.9 × 10^{-2}	9–14 × 10^{+2}	7.02 × 10^{-2}
Water consumption potential (kg/kg eq.)		2.99–5.36 × 10^{+4}	1.166–3.323 × 10^{+3}	-	8.86 × 10^{+2}	-	1.120 × 10^{+3}
Resource depletion (kg Sb eq.)		2.98–4.67 × 10^{-3}	0.9–4.1 × 10^{-4}	-	4.17 × 10^{-1}	-	4.64 × 10^{-3}
Energy consumption (MJ)		2.55–3.88 × 10^{+2}	-	1.71–7.06 × 10^{+2}	-	2.697–4.426 × 10^{+2}	-
Fossil fuel depletion (MJ)		1.26–1.77 × 10^{+1}	4.797–11.07 × 10^{+2}	1.7–6.9 × 10^{+1}	-	-	7.09 × 10^{+1}
Ozone depletion potential (kg CFC-11 eq.)×10^{-6}		2.33–3.07	0.8–1.5 × 10^{-1}	1.5–5	7.04	3.45–6.1 × 10^{-2}	9.6
Ionizing radiation potential (kBq U_{235} eq.)		1.62–2.27	-	8.0–14.5	2.60	-	5.0

* Calculated from H^+ mol eq.; Abbreviations: REO, Rare Earth Oxide; LREO, Light Rare Earth Oxide; HREO, Heavy Rare Earth Oxide.

Table A4. LCA of the production of REE from secondary materials.

Waste	**Bayan Obo Tailings**	**New Kankberg Tailings**	**Covas Tailings**	**Bayan Obo Tailings**	**Electronic**	**Magnet**	**Fluorescent Powders**	**Fluorescent Powder**
Reference	[48]	[59]	[59]	[30]	[61]	[57]	[62]	[57]
Country	Chine	Sweden	Sweden	Chine	USA		China	
1kg REO/REE to Be Extracted	Sc_2O_3	REO	REO	Sc_2O_3 + Other REO	REO	REO	REO	REO
Freshwater ecotoxicity potential (CTUe)	5.68 × 10^{+2}	-	-	4.11 × 10^{-1}	1.05–15.1 × 10^{+1}	1.8 × 10^{-2}	1.86 × 10^{+2}	2

Table A4. *Cont.*

Waste		Bayan Obo Tailings	New Kankberg Tailings	Covas Tailings	Bayan Obo Tailings	Electronic	Magnet	Fluorescent Powders	Fluorescent Powder
Acidification potential (kg SO_2 eq.)		$1.58 \times 10^{+1}$	-	-	1.44×10^{-3}	$8.73–113 \times 10^{-3}$	1.51×10^{-3} **	4.278×10^{-2}	1.89×10^{-3} **
Freshwater eutrophication potential (kg P eq.)		-	-	-	-	-	3×10^{-1}	3.9×10^{-4}	-
Terrestrial eutrophication potential (kg N eq.)		1.01	-	-	8.2×10^{-5}	$5.08–65.7 \times 10^{-3}$	8.0×10^{-3}	-	1.0×10^{-2}
Global warming potential (kg CO_2 eq.)		$3.940 \times 10^{+3}$	6.27×10^{-1} *	5.88 *	3.4×10^{-1}	1.81–21.7	6	$2.007 \times 10^{+1}$	$2.0 \times 10^{+1}$
Human toxicity potential	(CTUh)	2.56×10^{-6}	-	-	1.62×10^{-3}	$7.24–94.4 \times 10^{-7}$	2×10^{-5}	3.18×10^{-6}	1×10^{-6}
	(kg 1,4-DCB eq.)	-	7.7×10^{-12} *	1.92×10^{-9} *	-		-	-	-
Particulate matter formation potential (kg PM2.5 eq.)		4.51	-	-	4.7×10^{-4}	$6.94–107 \times 10^{-4}$	1.4×10^{-3}	7.0×10^{-3}	5×10^{-3}
Water consumption potential (kg/kg eq.)		$2.54 \times 10^{+5}$	-	-	-		$4.00 \times 10^{+2}$	$3.180 \times 10^{+3}$	$5.00 \times 10^{+2}$
Resource depletion (kg Sb eq.)		-	2.5×10^{-6} *	1.3×10^{-5} *	-		3.6×10^{-1}	-	4.5×10^{-5}
Energy consumption (MJ)		$1.01 \times 10^{+4}$	-	-	-		-	$1.784 \times 10^{+2}$	-
Fossil fuel depletion (MJ)		$2.655 \times 10^{+3}$	$1.567 \times 10^{+1}$ *	$1.37 \times 10^{+2}$ *	1.05	1.99–24.9	-		-
Ozone depletion (kg CFC-11 eq.) $\times 10^{-6}$		2.71	-	-	-	$5.12–99.6 \times 10^{-1}$	2.6×10^{-1}	1.596×10^{-1}	3×10^{-2}
Ionizing radiation potential (kBq U_{235} eq.)		-	-	-	-		2	$2.106 \times 10^{+1}$	3.5

* Calculated from normalized values based on global normalization factors, as described in Sala et al. (2017); ** calculated from H^+ mol eq. Abbreviations: REO, Rare Earth Oxide; LREO, Light Rare Earth Oxide; HREO, Heavy Rare Earth Oxide.

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