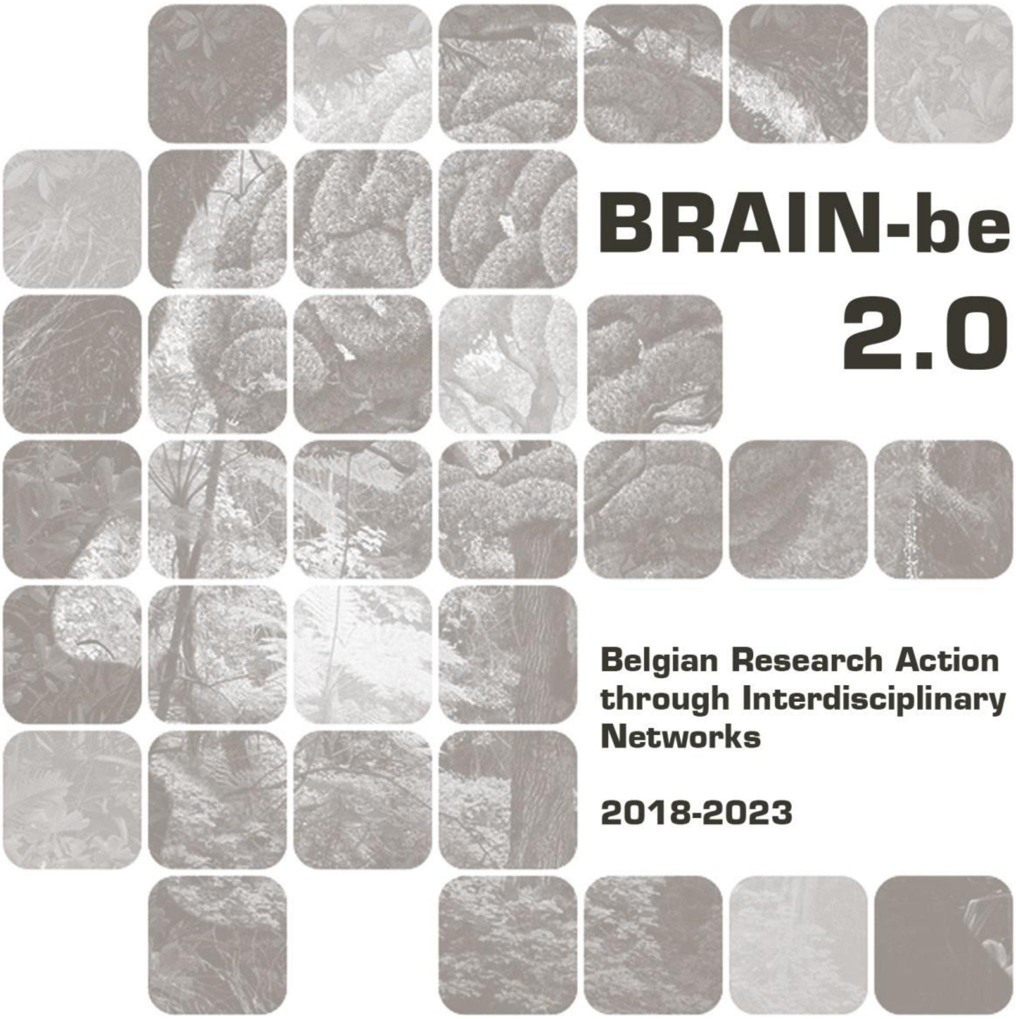

CAMBIUM

CirculAr Material flows in BelgIUM

WP3: Identification of the environmental and social impacts of Critical Raw Materials for Belgium

Alizé Carême, Dorine Hall (ICEDD)

Pillar 3: Federal societal challenges

NETWORK PROJECT

CAMBIUM

CirculAr Material flows in BelgIUM

Contract - B2/223/P3/CAMBIUM

WP3: Identification of the environmental and social impacts of Critical Raw Materials for Belgium

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ABSTRACT

Context

Critical raw materials (CRMs) have become a major concern in Europe and Belgium due to rapidly increasing demand driven by the green and digital transitions, combined with high supply risks linked to geographic concentration, geopolitical instability, and limited substitutability. While the first phase of the CAMBIUM project assessed criticality based on economic importance and supply risk, there is growing recognition that CRM supply chains also embed significant environmental, social and governance (ESG) challenges that are not captured by economic metrics alone.

Objectives

This report aims to complement the existing economic criticality assessment by integrating environmental, social and governance dimensions. It proposes a methodological framework to (i) identify ESG impact categories most frequently highlighted in mining-related literature, (ii) select and compute a set of proxy indicators reflecting these impacts at country level, and (iii) identify, among economically critical materials, those also associated with high ESG pressures along their extraction (Stage I) and processing (Stage II) supply chain segments supplying the EU market.

Conclusions

A targeted review of 70 scientific articles structured mining-related impacts into 15 broad categories, of which five emerge as most prominent: land use and territorial change; environmental health and pollution affecting air, soil and water; employment and livelihoods; human health, security and safety; and economy, income and inequality. Building on these priorities, 25 indicators were compiled from international databases (World Bank ESG DataBank, OECD, UNICEF) and calculated for 74 raw materials using weighted aggregation based on country shares in EU supply chains (JRC, 2020), separately for extraction and processing. Because defining universal ESG criticality thresholds is methodologically and ethically challenging, a relative approach was applied by identifying the worst-performing materials for each indicator. Results show that among the 35 raw materials identified as economically critical for the European market, 32 are also associated with significant environmental and/or social pressures in their supply chains. Overall, the findings demonstrate that economic criticality alone does not reflect the full range of sustainability and governance challenges embedded in CRM supply, highlighting the value of a multidimensional approach to support more resilient and sustainability-oriented policy decisions.

Keywords

Critical raw materials (CRM)
Economic importance
Supply Risk

1. INTRODUCTION

In recent years, the issue of critical raw materials (CRMs) has gained increasing attention in both European and national policy contexts. The accelerating demand for minerals and metals driven by the green and digital transitions, such as those used in renewable energy technologies, electric mobility, and advanced electronics, has intensified concerns over the long-term availability of these resources. Many of these materials are scarce, geographically concentrated, or extracted under unstable socio-political conditions, which exposes supply chains to significant risks. Identifying and monitoring CRMs is therefore essential to ensure the security of supply, support industrial competitiveness, and guide strategic actions toward a more sustainable and resilient material economy.

Following the identification of critical materials for Belgium in Task 1 – based on the European Commission's methodology and focused on economic importance and supply risk – this second phase of **the study aims to broaden the assessment of material criticality by integrating social and environmental dimensions.** The purpose of this task is to identify relevant impact categories and indicators that reflect the social and environmental consequences of raw material production and supply, thereby contributing to a more comprehensive and sustainability-oriented criticality analysis for Belgium. In this context, the results of this task will support policy development and decision-making regarding the most critical material flows, as well as the products and economic activities that depend on them.

The integration of environmental and social aspects into criticality assessments responds to the growing recognition that the supply of raw materials is not only an economic or technological issue, but also a matter of environmental protection and social well-being. Many of the United Nations Sustainable Development Goals (SDGs) for 2030 depend on the contribution of minerals and metals, which drive manufacturing industries, create employment, and generate added value along global supply chains. At the same time, however, mineral production often results in adverse environmental and social effects, potentially hindering progress toward other goals such as climate action, good health, and clean water. This duality underscores the importance of developing an integrated understanding of the impacts associated with the extraction and processing of raw materials.

From an environmental perspective, the mining and processing of primary raw materials, such as ores, industrial minerals, and aggregates, inevitably entail disturbances to natural systems. These activities can reshape landscapes, destroy ecosystems, and affect soil, air, and water quality. The type and magnitude of these impacts vary widely depending on the mineral extracted, the geological setting, and the extraction and processing methods applied. While numerous studies have investigated specific cases of mining-related environmental damage, the lack of consistent and comparable evaluation frameworks makes it difficult to account for these impacts in material criticality assessments. Moreover, conventional assessment methods such as life-cycle analysis often fail to capture key mining-related concerns, including land use, biodiversity loss, and water consumption, due to limited methodological coverage and poor data availability. In practice, these limitations hinder a robust consideration of environmental risks within the criticality debate.

Social aspects of mining are equally complex and increasingly recognized as crucial for the long-term sustainability of the raw materials sector. Environmental degradation, poor working conditions, and unequal benefit sharing can undermine the social acceptability of mining projects and contribute to local conflicts. Social performance is further influenced by economic dependency on the mining sector, which can expose communities to price volatility and boom-bust cycles. Strengthening the social sustainability of mining has therefore become a key objective for industries seeking to enhance transparency, trust, and legitimacy. This trend is reflected in the growing adoption of corporate social responsibility (CSR) frameworks and reporting standards such as the Global Reporting Initiative (GRI), which encourage companies to disclose their social and environmental performance. Beyond physical and economic impacts, mining activities can also reshape inhabited spaces and generate psychological and social changes among workers and surrounding communities, affecting livelihoods, well-being, and perceptions of territory.

Following the presentation of the objectives, the report outlines the general methodological framework, including key methodological choices, underlying assumptions and specific clarifications relevant to its design. The results of the literature-based prioritisation of impact categories, as well as the indicators calculated for a set of 74 raw materials, are then presented and discussed. Finally, methodological recommendations are proposed in the form of potential avenues for further refinement and improvement of the framework.

2. OBJECTIVES

Against this background, **the present report aims to complement the existing economic assessment of criticality by identifying which critical raw materials are associated with significant environmental, social and governance impacts embedded within their supply chains.** Building on the criticality assessment conducted in Task 3.1 of the CAMBIUM project, which focuses on economic importance and supply risk, this work seeks to broaden the scope of criticality analysis by incorporating non-economic dimensions relevant to sustainable and resilient raw material supply.

The objective of this task is therefore to propose a methodological framework for extending material criticality assessments to include environmental, social and governance aspects. This framework is based on a structured review of scientific and policy-oriented literature to identify the main impacts of mining activities, combined with the calculation of indicators that capture, or act as proxies for, these impacts along raw material supply chains serving the European and Belgian markets.

More specifically, the objectives of this task are threefold. First, it aims to identify the environmental, social and governance impact categories most frequently discussed in the literature as being associated with the mining sector. Second, it seeks to select and calculate a set of indicators that allows for the estimation of these impacts at the country level, reflecting the conditions under which critical raw materials are extracted and processed in the countries contributing to European supply chains. Third, based on the results of these indicators, the analysis aims to identify, among the raw materials already classified as economically critical in Task 3.1, those that are additionally associated with significant environmental, social and/or governance issues in their supply chains, particularly for impact categories identified as prominent in the literature.

Ultimately, by highlighting raw materials that are critical not only from an economic perspective but also from environmental, social and governance standpoints, this report contributes to a more comprehensive understanding of the multidimensional risks associated with raw material supply. Such an integrated perspective is intended to support policy-relevant decision-making and to inform strategies aimed at enhancing the sustainability and resilience of raw material supply chains in Belgium and the European Union.

3. METHODOLOGY

3.1 General framework

The criticality assessment conducted for Belgium in the first part of this work package (task 3.1) identified a subset of materials falling within the criticality zone, characterized by high scores in both economic importance and supply risk (see *WP3: Identification of the critical materials for Belgium – report on the criticality assessment*).

To further identify the most critical material flows for Belgium, beyond the sole consideration of economic importance and supply risk, this task extends the criticality assessment by integrating environmental and social dimensions. In particular, it examines the environmental and social impacts associated with the extraction and processing of critical raw materials in the countries where these activities take place, thereby capturing upstream impacts embedded in CRM supply chains. The analysis focuses on country-level conditions as a proxy for the environmental and social pressures linked to the production of CRMs.

The selection of relevant environmental, social and governance dimensions was informed by a targeted review of scientific and policy-oriented literature identifying the main impact categories associated with the mining sector. This screening drew in particular on the impact categorisation proposed by Mancini and Sala (2018) and on the material topics identified in the Global Reporting Initiative (GRI) sector-specific standard for mining (2024). Together, these frameworks provided a structured overview of the environmental, social and governance impact areas most associated with mining activities. This preliminary step enabled to delineate the categories of impacts to be considered and, in turn, to guide the identification of relevant indicators and data sources for the subsequent quantitative analysis.

Environmental, social and governance indicators were collected from international databases, primarily the World Bank Environmental, Social and Governance (ESG) databank and the OECD databank. For each critical raw material, indicator values were computed as a weighted sum of country-level indicators, where the weights correspond to each country's share in the extraction or processing stages of the CRM supply chain supplying the EU market. The relative contribution of each country to the supply chain of each CRM was found in the study on the EU's list of Critical Raw Materials (European Commission, 2020). This approach ensures that countries with a larger role in the extraction or processing stages of a given CRM have a proportionally greater influence on the aggregated indicator value. This approach is based on the assumption that CRMs predominantly extracted or processed in countries facing significant governance, environmental or social challenges are associated with higher embedded environmental and social impacts than those sourced from countries with more robust institutional and regulatory frameworks.

The indicators were calculated for two distinct stages of the value chain:

- Stage 1 – Extraction: country weights correspond to the share of primary extraction supplying the EU market.
- Stage 2 – Processing: country weights correspond to the share of processing activities supplying the EU market.

For each indicator and each CRM, a weighted sum is computed as follows:

$$Indicator_{CRM} = \sum(w_i \times indicator_i)$$

where w_i is the share of country i in the relevant stage of the CRM supply chain, and $indicator_i$ is the value of the indicator for country i.

For several indicators, data coverage was incomplete and country-level values were missing for a subset of countries. In such cases, proxy values were assigned by calculating the arithmetic mean of the available country-level observations and attributing this mean value to countries with missing data.

A key methodological challenge concerned the definition of criticality thresholds for the environmental and social indicators. Defining a universal threshold beyond which a material would be considered "critical" proved difficult, as such thresholds often raise normative and ethical questions and may be highly context-dependent. While certain indicators lend themselves more easily to threshold-based interpretation, such as air pollutant emissions, for which regulatory limits exist at European and international levels, or child labour, for which no non-zero level can be considered acceptable, many others do not. For example, indicators related to land use change or tree cover loss raise the question of how much change can reasonably be considered critical. Similarly, defining an acceptable number of years of life lost or impaired due to environmental or social impacts is inherently subjective.

In light of these limitations, a relative approach was adopted. For each indicator, the CRMs displaying the highest values were identified and classified as the "worst performers" for that specific impact category. This approach avoids the introduction of arbitrary or subjective thresholds and allows for a transparent identification of materials associated with relatively high environmental or social pressures for each indicator.

In total, 25 indicators were evaluated for each critical raw material, resulting in a diverse set of worst-performing materials depending on the impact category considered. To ensure consistency and comparability across indicators and materials, all calculations were performed using harmonised datasets and a common aggregation framework, and the same methodological choices were applied systematically across all CRMs and value-chain stages considered.

Finally, a literature review was conducted to support the prioritisation of indicators based on their relevance in the scientific literature. The review focused on identifying the most significant environmental and social impacts associated with the mining sector and their broader implications. A total of 70 peer-reviewed scientific articles were analysed to determine which impact categories are most frequently highlighted as critical in relation to mining activities.

3.2 Indicators

Environmental, social and governance indicators were compiled and calculated for each critical raw material.

3.2.1 Environmental indicators

The following environmental indicators were computed for each CRM:

- **Net land cover change.** This indicator is derived from a global land cover dataset designed to monitor pressures on ecosystems and biodiversity through changes in land cover. It measures the net change in natural and semi-natural vegetated land, with positive values indicating a net gain in vegetated land area and negative values indicating a net loss. It is measured in square kilometres (km²) and was calculated using the most recent data available for each country. Absolute land cover change was preferred to relative (percentage-based) measures in order to better capture the physical magnitude of land transformation potentially associated with mining and processing activities. The indicator is based on data available on the OECD Data Explorer, coming from the Climate Change Initiative land cover dataset and the Global Human Settlement Layer built-up area dataset. It relies on high-resolution geospatial data to produce internationally comparable indicators over long time horizons, with five-year intervals covering 2000-2022 for the Climate Change Initiative Land Cover dataset and 1975-2030 for the Global Human Settlement Layer dataset. Data is available globally at the national level, with additional sub-national (TL2) coverage for OECD countries and selected non-OECD countries.

- **Natural resource depletion** represents the combined depletion of forest, energy and mineral resources. Net forest depletion is estimated as resource rents multiplied by the excess of roundwood harvest over natural growth. Energy depletion reflects the value of remaining energy resource stocks (coal, crude oil and natural gas) relative to their estimated reserve lifetime, capped at 25 years. Mineral depletion is calculated similarly and covers a range of minerals, including metals and industrial minerals. This indicator is expressed as a percentage of Gross National Income (GNI) and was calculated using the most recent available value for each country. Expressing depletion as a share of GNI allows the indicator to reflect the economic significance of natural resource extraction. Data are sourced from World Bank estimates and the Changing Wealth of Nations framework.
- **Tree cover loss**. Tree cover loss represents the annual stand-replacement loss of tree cover exceeding five metres in height within a given area. This indicator is measured in hectares and was calculated using the most recent available value for each country. The indicator captures loss of both natural and planted tree cover and does not exclusively reflect deforestation or human-induced change. From 2011 onwards, an updated methodology was applied, potentially capturing additional loss. The dataset, coming from the Environment Social and Governance (ESG) database available on DataBank website, is produced through a collaboration between the University of Maryland, Google, USGS and NASA, and is based on Landsat satellite imagery with a spatial resolution of 30 × 30 metres. Data is sourced from Global Forest Watch.
- **Freshwater use**. This indicator captures freshwater use directly attributable to mining activities. It is measured in cubic metres and was calculated using the most recent available value for each country. The indicator is derived from national-level data on water made available for use on the OECD Data Explorer, disaggregated by sector. Its interpretation requires caution due to differences in national definitions and reporting practices. Data is sourced from the Joint OECD/Eurostat Questionnaire on Inland Waters, with data for non-OECD countries obtained from the United Nations Statistics Division.
- **Level of water stress**. It corresponds to the ratio of total freshwater withdrawals by all major economic sectors to total renewable freshwater resources, after accounting for environmental flow requirements. Major sectors include agriculture, forestry and fishing, manufacturing, electricity generation and services, as defined by ISIC standards. This indicator is expressed as the percentage of total freshwater withdrawals relative to available renewable freshwater resources and was calculated using a fixed reference year (2021, as it is the most recent year with data for all considered countries). The level of water stress, also referred to as water withdrawal intensity,

is sourced from FAO AQUASTAT, the Global Information System on Water and Agriculture, and data was collected from the Environment Social and Governance (ESG) database.

- **Annual Freshwater Withdrawals** correspond to total water abstracted for agricultural, industrial and domestic uses, excluding evaporation losses from storage basins. Withdrawals include water sourced from desalination plants when relevant, and may exceed 100% of renewable water resources in countries relying on non-renewable aquifers, desalination or significant water reuse. This indicator is expressed as a percentage of internal renewable freshwater resources and reflects the level of pressure exerted on national water systems. A fixed reference year (2021) was used for all countries (2021 being the most recent year with data for all considered countries). Annual freshwater withdrawals. Data is sourced from FAO AQUASTAT, the Global Information System on Water and Agriculture, and are available on DataBank website (Environment Social and Governance (ESG) database).
- **Air pollutant emissions – SO_x and NO_x**. This indicator covers anthropogenic emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x), reported under the NFR 2014 classification. Emissions from international aviation and maritime transport, as well as non-anthropogenic sources, are excluded. It is normalized, expressed in kilograms per 1,000 USD of economic output and was calculated using the most recent available value for each country. Normalisation by economic output enables comparisons across countries of different economic sizes and captures pollution intensity rather than absolute emission levels. The data was collected on the OECD Data Explorer and is compiled from the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP) emissions database, Common Reporting Tables submitted to the UNFCCC, and responses to the OECD Questionnaire on the State of the Environment, complemented by country-specific comments.
- **Greenhouse gas emissions**. This indicator covers anthropogenic emissions of major greenhouse gases, including CO_2, CH_4, N_2O and fluorinated gases (HFCs, PFCs, SF_6 and NF_3), with CO_2 emissions originating from energy use and industrial processes and CH_4 emissions including those from coal and lignite mining. Indirect CO_2 emissions are excluded. It is expressed in kilograms of CO_2-equivalent per 1,000 USD of economic output and was calculated using the most recent available value for each country. It captures the greenhouse gas emission intensity associated with mining activities, as data was available at the sector-level on the OECD Data Explorer. Data is sourced from National Inventory Submissions to the UNFCCC.
- **Mining waste generated**. This indicator is measured in tonnes and captures the quantity of waste generated by mining activities. The most recent available value was used for each country. The indicator is based on national-level data on waste generation by economic sector, classified according to the major divisions of the International Standard Industrial Classification (ISIC), Revision 4. Data, obtained from the OECD Data Explorer, is compiled from multiple sources, including the OECD State of the Environment Questionnaire on Waste for non-EU countries, the EU Waste Framework Directive as reported in the Eurostat database for EU Member States, and country-level data collected by the United Nations Statistics Division (UNSD) in collaboration with UNEP for non-OECD countries.

3.2.2 Social Indicators

Social dimensions of CRM supply chains were captured through the following indicators:

- **Child labour.** This indicator measures the share of children aged 5-17 engaged in child labour and reflects structural risks related to labour rights and social conditions. Child labour is defined based on children's involvement in economic activities or excessive unpaid household services. Thresholds vary by age group and include minimum hours of economic activity for children aged 5-17, as well as time spent on unpaid household chores for children aged 5-14. The indicator is expressed as a percentage of the child population and was calculated using the most recent available value for each country, irrespective of the reference year, given the persistent nature of child labour risks. Data are compiled by UNICEF based on nationally representative household surveys and were extracted from the UNICEF website.

- **Gini index.** The Gini index measures income inequality within a country by quantifying the deviation of income (or consumption expenditure) distribution from perfect equality. It is derived from the Lorenz curve and reflects the extent to which income is unevenly distributed across individuals or households. The indicator ranges from 0, indicating perfect equality, to 100, indicating maximum inequality, and was calculated using the most recent available value for each country. Data are based on harmonised household survey data and were extracted from the Environment Social and Governance (ESG) database on the World Bank data website.
- **Economic and social rights performance score.** This composite indicator captures countries' performance in ensuring key economic and social rights. It evaluates how effectively a country realises core economic and social rights (education, food, health, housing and work) given its level of national income, and therefore reflects the extent to which populations are able to access basic goods, services and opportunities necessary for well-being, relative to a country's level of resources. A higher score indicates better performance in fulfilling these rights relative to what could be expected at that income level, while a lower score reflects less effective use of available resources to realise them. The indicator is expressed as a standardised score and was calculated using the most recent available value for each country. The indicator is developed by the Human Rights Measurement Initiative (HRMI) and based on the SERF Index methodology. Data are produced by the HRMI and were extracted from the Environment Social and Governance (ESG) database on the World Bank data website.
- **Mortality, morbidity and welfare cost from environmental risks.** This indicator captures population-level health impacts associated with exposure to environmentally related and occupational risk factors that are particularly relevant to mining activities. It reflects the combined burden of premature mortality and morbidity attributable to environmental and occupational exposures. CRMs sourced from countries where per-capita environmental health impacts are high are associated with higher health risks. The indicator is expressed in Disability-Adjusted Life Years (DALYs) per 1,000 inhabitants and was calculated using a fixed reference year (2019, the most recent year with complete data coverage). Six risk-specific sub-indicators were considered separately: ambient particulate matter ($PM_{2,5}$), lead exposure, occupational carcinogens, occupational particulate matter, gases and fumes, unsafe water sources, and occupational noise. Data are sourced from the OECD database on mortality, morbidity and welfare costs from exposure to environmental risks and were extracted from the OECD Data Explorer.

3.3.3 Governance indicators

Governance quality was assessed using the six Worldwide Governance Indicators (WGIs), which capture different dimensions of institutional quality relevant to the environmental and social performance of CRM supply chains. For each dimension, governance standardized scores are expressed on a scale ranging from -2.5 to +2.5, with higher values indicating better governance performance. The six WGIs were calculated using the most recent available value for each country over the 2020-2024 period. Data were extracted from the Worldwide Governance Indicators available through the World Bank data platform. CRM-level governance indicators were computed through weighted aggregation, using the same country weights as those applied for environmental and social indicators.

- **Voice and accountability.** This indicator reflects the extent to which citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association and the presence of a free media. It captures fundamental aspects of democratic governance and civil liberties.
- **Political stability and absence of violence.** This indicator measures perceptions of the likelihood of political instability and politically motivated violence, including terrorism. It reflects the degree to which governments are threatened by unconstitutional or violent means.
- **Government effectiveness.** This indicator captures perceptions of the quality of public services, the quality and independence of the civil service, the quality of policy formulation and implementation, and the credibility of the government's commitment to its policies. It reflects the capacity of the state to design and implement effective public policies.
- **Regulatory quality.** This indicator measures perceptions of the ability of governments to formulate and implement sound policies and regulations that support private sector development. It reflects the quality of the regulatory environment in which economic activities take place.
- **Rule of law.** This indicator captures perceptions of the extent to which individuals and institutions have confidence in and abide by the rules of society. It encompasses the quality of contract enforcement, property rights, the police and the courts, as well as the prevalence of crime and violence.
- **Control of corruption.** This indicator reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the capture of the state by elites and private interests. It provides an assessment of corruption risks affecting governance quality.

3.3 Data sources and temporal treatment of data

Three primary databases were used for this analysis: the World Bank Environment, Social and Governance (ESG) database, the OECD Data Explorer, and the UNICEF database. For each indicator, missing values were observed for a subset of countries, and the temporal coverage of the data also differed across countries. For instance, a given indicator may be available for one country in year *A*, while for another country it is only available in year *B*. This heterogeneity motivated the use of the most recent available value for each country and each indicator, based on the assumption that the indicator does not change abruptly over short time horizons. While this assumption is non-trivial, it allows the use of country-specific values rather than assigning a global average to countries for which data exist but for a different reference year.

Country-level shares for the extraction and processing of critical raw materials were taken from European trade data. These shares were sourced from the European Commission Joint Research Centre (JRC) 2020 report on EU critical raw materials, which provides estimates of the countries contributing to the extraction (stage 1) and processing (stage 2) of CRMs supplying the European market. Using these data ensures consistency with the economic criticality assessment, as it relies on the same EU trade-based information to characterise CRM supply chains.

For consistency with the methodology applied by the JRC in its 2020 and 2023 assessments, most critical raw materials were treated individually in the analysis, while a limited number were grouped into material categories. This is the case for Heavy Rare Earth Elements (HREEs), which include dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium and yttrium; Light Rare Earth Elements (LREEs), comprising cerium, lanthanum, neodymium, praseodymium and samarium; and Platinum Group Metals (PGMs), which include iridium, palladium, platinum, rhodium and ruthenium.

A specific methodological exception was applied for cerium at the extraction stage (Stage 1). In line with the country-level shares reported in the JRC 2020 dataset used in this task of the CAMBIUM project, cerium exhibited distinct extraction-country shares compared to lanthanum, neodymium, praseodymium and samarium, which share identical extraction profiles. Cerium was therefore treated as an individual material for the extraction stage (stage I). At the processing stage (Stage II), however, cerium shares the same country-level processing data as the other LREEs and was consequently included within the LREE group for the Stage II analysis.

3.4 Country coverage and proxy

The set of countries covered varies across indicators, depending on data availability in the underlying datasets.

For countries with no available data for a given indicator, proxy values were computed using the arithmetic mean of the most recent available country-level observations across all countries covered by the dataset, irrespective of the reference year. Restricting proxy values to a single reference year would have resulted in a substantial loss of information and introduced a systematic bias towards countries with more recent statistical reporting, typically high-income economies. The adopted approach therefore ensures broader country coverage while remaining consistent with the “latest available value” rule applied to countries with observed data.

3.5 Literature review and prioritisation

In order to identify the most relevant social and environmental impacts of the mining sector, and thereby support the selection and prioritisation of indicators among those calculated in this study, a targeted literature review was conducted. The objective of this review was not to develop new indicators, but to assess which impact categories are most prominently discussed in the scientific and policy-oriented literature and should therefore be considered as priorities when extending material criticality assessments to social and environmental dimensions.

Mancini and Sala (2018) identified 28 impact categories related to social and economic aspects, which they grouped into 6 broader categories: Economy, Income, and Security; Employment and Education; Land Use and Territorial Aspects; Demography; Environment, Health, and Safety; and Human Rights. This classification provided a first structured framework for identifying the main areas of concern associated with mining activities.

In addition, the Global Reporting Initiative (GRI) published a report on the mining sector in 2024, identifying key “material topics” relevant to the industry. For each topic, the report outlines the most significant impacts associated with mining activities and specifies recommended disclosures for reporting by mining organisations. The GRI framework highlights 25 material topics representing key domains in which mining activities may generate social, environmental, or economic impacts. These include greenhouse gas emissions; climate adaptation and resilience; air emissions; biodiversity; waste and tailings; water and effluents; mine closure and rehabilitation; economic impacts; local communities; rights of Indigenous Peoples; land and resource rights; artisanal and small-scale mining (ASM); security practices; critical incident management; occupational health and safety; employment practices; child labour; forced labour and modern slavery; freedom of association and collective bargaining; non-discrimination and equal opportunity; anti-corruption; payments to governments; public policy; and activities in conflict-affected or high-risk areas. These categories were used as an additional reference framework to inform the identification of priority impact categories in this study.

Together, the frameworks proposed by Mancini and Sala (2018) and the GRI (2024) provided a comprehensive basis for identifying impact categories relevant to the mining sector. This basis was expanded in order to capture a broader range of social and environmental concerns. For this purpose, the original review by Mancini and Sala (2018) was extended with 22 further studies, resulting in a total of 72 scientific articles reviewed. Finally, this extended review enabled to assess the extent to which different impact categories defined by Mancini and Sala (2018) and by the GRI (2024) are represented and discussed across the scientific literature.

Based on this review, 15 broad impact categories were identified, encompassing both social, environmental and governance dimensions of the mining sector. Together, these categories cover a total of 84 specific impacts or subcategories, which represent areas of concern rather than directly operational indicators. These impact subcategories provided a conceptual basis for identifying the types of data and indicators to be sought in international databases, ultimately leading to the selection and calculation of the 25 indicators used in this analysis.

Prioritisation of impact categories, and corresponding indicators among those calculated, was primarily based on the prominence of each impact category in the scientific literature, measured by the frequency and emphasis with which these impacts are discussed across the reviewed studies. While this approach is inevitably influenced by research trends and potential biases within the literature, it nevertheless provides a consistent and transparent basis for identifying impacts that are widely recognised as significant or problematic at the global level. The prioritised impact categories were subsequently used to guide the interpretation and emphasis of the environmental, social and governance indicators calculated in this study.

4. STATE OF THE ART

The state of the art builds primarily on the work of Mancini and Sala (2018), who conducted a review of 50 scientific articles comparing social impact indicators applied to the mining sector. Their analysis identified 28 distinct impact categories, which were grouped into 6 broader domains: economy, income and security; employment and education; land use and territorial aspects; demography; environment, health and safety; and human rights. This framework provides a structured and widely cited reference for assessing the social dimensions of mining activities.

In addition, the sector-specific recommendations published by the Global Reporting Initiative (GRI) for the mining industry were used to complement and extend this framework. The GRI report identifies a set of “material topics” considered most relevant to the mining sector, encompassing environmental, social and governance dimensions. These material topics include: greenhouse gas emissions; climate adaptation and resilience; air emissions; biodiversity; waste; tailings; water and effluents; closure and rehabilitation; economic impacts; local communities; rights of Indigenous Peoples; land and resource rights; artisanal and small-scale mining; security practices; critical incident management; occupational health and safety; employment practices; child labour; forced labour and modern slavery; freedom of association and collective bargaining; non-discrimination and equal opportunity; anti-corruption; payments to governments; public policy; and conflict-affected and high-risk areas. These predefined material topics were used as a reference framework to identify and structure impact categories relevant to the mining sector.

Building on these 2 reference frameworks, an additional literature review was conducted to further refine the impact categorization and to assess the relative prominence of different impact categories in the scientific literature. In total, 22 additional studies were reviewed, which are listed in Table 1. This extended review enabled to identify impact categories that were not explicitly covered by Mancini and Sala (2018) or by the GRI framework, as well as to confirm or nuance the importance of categories already identified.

Based on this expanded body of literature, the initial set of impact categories was reorganized, with certain categories being split or merged where appropriate. These adjustments were made to better reflect how impacts are discussed in the literature and to facilitate a consistent assessment of their prominence and relative importance. The resulting impact categorisation, ordered according to its frequency of occurrence in the reviewed studies, is presented in the Results section.

Table 1. List of studies selected from the literature and main features

Author	Publication year	Type of document	Title	Country coverage	Publication
Ahemd, Dr Sameh and Tahlawi, M.R.	2011	Research article	Environmental Impacts of Mining Operations: a Case Study: Monitoring the Impacts of Abu Tartour Phosphate Mine, Egypt	Egypt	The International Journal of Environmental Protection (IJEP). 1. 1-6.
Boldy R. et al.	2021	Research article	Understanding the impacts of mining on ecosystem services through a systematic review	/	The Extractive Industries and Society. Volume 8, Issue 1, Pages 457-466(https://doi.org/10.1016/j.exis.2020.12.005)
Bouchard-Batsien E. and Gervais M.C.	2017	Knowledge synthesis	Dimensions sociales et psychologiques associées aux activités minières et impacts sur la qualité de vie	Québec, Canada	Government of Quebec -Institut national de santé publique du Québec (ISBN:978-2-550-79786-9)
Crona B. et al.	2023	Research article	Going beyond carbon - An Earth system impact score to better capture corporate and investment impacts on the earth system	World	Journal of Cleaner Production. Volume 429, 139523 (https://doi.org/10.1016/j.jclepro.2023.139523)
Eheliyagoda D. et al.	2020	Research article	A method to assess national metal criticality : the environment as a foremost measurement	China	Humanit Soc Sci Commun 7, 43 (https://doi.org/10.1057/s41599-020-00537-4)
Environmental Law Alliance Worldwide (ELAW)	2010	Book	Guidebook for Evaluating Mining Project EIAs	/	ISBN:978-0-9821214-36
Mononen T. et al. - European Parliament's Committee on Petitions	2022	Institution report	Social and environmental impacts of mining activities in the EU	EU	ISBN 978-92-846-9361-0 | doi: 10.2861/804163
Giljum et al.	2022	Research article	A pantropical assessment of deforestation caused by industrial mining	World + Indonesia, Brazil, Ghana, and Suriname	PNAS 2022 Vol. 119 No. 38 e2118273119 (https://doi.org/10.1073/pnas.2118273119)
Global Reporting Initiative	2024	Institution report	GRI 14: Mining Sector 2024	/	ISBN 978-90-8866-140-2
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2023	Institution report - Case study	The Importance of Consultation and Engagement in Environmental and Social Impact Assessments	/	https://www.igfmining.org/fr/resource/case-study-the-importance-of-consultation-and-engagement-in-environmental-and-social-impact-assessments/
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2022	Institution report - Case study	Biodiversity and Mining Governance: Senegal and Turkey	Senegal and Turkey	https://www.igfmining.org/resource/biodiversity-and-mining-governance-senegal-and-turkey/
IGF (Intergovernmental Forum on Mining, Minerals, and	2022	Institution report - Case study	Inclusive Closure and Post-Mining Transition at the Golden Pride Mine, Tanzania	Tanzania	https://www.igfmining.org/resource/inclusive-closure-and-post-mining-transition-at-the-golden-pride-mine-tanzania/

Sustainable Development)					
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2022	Institution report - Case study	Regulatory Continuous Improvement: Lessons from British Columbia's new statutory audit function's application to mine tailings facilities	British Columbia, Canada	https://www.igfmining.org/resource/regulatory-continuous-improvement-lessons-from-british-columbias-new-statutory-audit-functions-application-to-mine-tailings-facilities/
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2021	Institution report - Case study	Mine Waste Management: Case studies from Ghana and Canada	Ghana and Canada	https://www.igfmining.org/resource/mine-waste-management-case-studies-from-ghana-and-canada/
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2021	Institution report - Case study	Mine Water Management: Case studies from Mongolia and Chile	Mongolia and Chile	https://www.igfmining.org/resource/mine-water-management-case-studies-from-mongolia-and-chile/
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2021	Institution report - Case study	Mine Closure Policies in South America	South America	https://www.igfmining.org/resource/mine-closure-policies-in-south-america/
IGF (Intergovernmental Forum on Mining, Minerals, and Sustainable Development)	2019	Institution report - Case study	Skills Building for Women in Artisanal and Small-Scale Mining	/	https://www.igfmining.org/resource/skills-building-for-women-in-artisanal-and-small-scale-mining/
Leyton-Flor and Sangha	2024	Research article	The socio-ecological impacts of mining on the well-being of Indigenous Australians - A systemic review	Australia	The Extractive Industries and Society, Volume 17, 101429 (https://doi.org/10.1016/j.exis.2024.101429)
Mancini and sala	2018	Research article	Social impact assessment in the mining sector: Review and comparison of indicators frameworks	/	Resources Policy, Volume 57, Pages 98-111 (https://doi.org/10.1016/j.resourpol.2018.02.002)
Murray and Paquet	2014	Poster	Revue de littérature sur les impacts environnementaux et les mesures d'atténuation reliés à l'exploration et à l'exploitation de mines d'uranium	Québec, Canada	https://doi.org/10.13140/RG.2.1.3345.0480
Norgate and Haque	2010	Research article	Energy and greenhouse gas impacts of mining and mineral processing operations	/	Journal of Cleaner Production, Volume 18, Issue 3, Pages 266-274 (https://doi.org/10.1016/j.jclepro.2009.09.020)

OECD	2012	Institution report	Strategic Environmental Assessment in Development Practice: A Review of Recent Experience - Chapter 8 Sierra Leone: Strategic Environmental and Social Assessment of the mining sector	Sierra Leone, Africa	OECD Publishing (ISBN 978-92-64-16674-5 | http://dx.doi.org/10.1787/9789264166745-en)
Responsable Mining Foundation	2021	Institution report	Harmful Impacts of Mining : when extraction harms people, environments and economies	World	https://www.responsibleminingfoundation.org/harmful-impacts-mining/
Rodrigues et al.	2017	Research article	Methodology for the Assessment of the Ecotoxicological Potential of Construction Materials	/	Materials 2017, 10, 649; doi:10.3390/ma10060649

5. RESULTS

5.1 Prioritisation of impact categories based on the literature

This subsection presents the results of the literature review used to identify and prioritize the most significant environmental, social and governance impact categories associated with the mining sector. Based on the literature review, the environmental, social and governance impact categories associated with mining activities are ranked from the most to the least prominent (according to their frequency of occurrence) in the reviewed studies as presented in the following table.

Table 2. Main environmental, social and governance impact categories of mining activities

Impact category	Type of impact			Underlying aspects
	Social	Envir.	Gov.	
1. Land use (change) impacts and territorial aspects	X	X		• Improved infrastructures • Expropriation and displacement (local communities) • Access (and relationship) to land (local communities) • Land use change (cultural and social impact) • Land and resource rights and competition • Land use, landscape, topography change • Erosion • Land use emissions • Alteration of soil profiles and soil degradation • Risk of contamination (soils, soil quality) • Deforestation
2. Environmental health and Pollution (management) (air-soil-water)	X	X		• Risk of contamination (soil, water) • Ecotoxicology • Nitrogen oxides (NOx), sulfur oxides (SOx), and other significant air pollutants • Air quality and dust
3. Employment, education and wel-being/livelihoods	X			• Increased employement • Skills and education • Chilled and forced labour • Poor working conditions, occupational health and safety • Lack of freedom (to organize in Trade Unions) and non-conformity with the requirements of the International Labour Organization conventions • Temporary jobs • (Indigenous) people's well-being (including livelihood) • Unemployement
4. Human health, security and safety	X			• Security practices and impacts (presence of security in the mine) • Thefts, accidents and deaths • Health and safety impacts • Noise, vibration and light pollution impacts • Environmental impacts affecting health

5. Economy, income & inequality	X			• Income and inequality • Tax income, royalties • Business and employment opportunities (in other sectors due to revitalized economy and markets) • Adverse economic outcome, increased poverty • Impacts on other economic sectors
6. Human rights	X			• Cultural and aesthetic resources • Stakeholders inclusion (local communities) • Violence and gender-related issues (rape, sexual assault and harassment) • Discrimination • Indigenous rights
7. Governance, administration and public policy			X	• Political stability and absence of violence • Rule of law • Government effectiveness • Voice and accountability • Transparency and accountability • Bribery and corruption control • Social tensions and conflicts • Regulatory quality
8. Biodiversity & ecosystems		X		• Biodiversity impacts (loss, fragmentation, habitat changes, …) • Changes to the state of biodiversity (incl. deforestation) • Ecosystem services and conservation/ degradation
9. Demography	X			• Population growth • Gender imbalance and migration in mining communities • Inflation
10. Water and effluents		X		• Interactions with water as a shared resource • Water use competition and access to water • Management of water discharge-related impacts • Water management policy • Water withdrawal • (Waste) Water discharge (impacts) • Change in hydrology • Ground and surface water impacts • Water quality (change and pollution) • Water scarcity • Water consumption
11. Waste (management) and tailings		X		• Waste generation and significant waste-related impacts • Waste management policy and management of significant waste-related impacts • Waste generated • Waste directed to and diverted from disposal (recycled, reuse, ...) • Tailings

12. Greenhouse gas (GHG) emissions		X		• Direct (Scope 1) GHG emissions • Energy indirect (Scope 2) GHG emissions • Other indirect (Scope 3) GHG emissions • GHG emissions intensity • Lost in CO2 uptake (deforestation related) • Reduction of GHG emissions
13. Closure and rehabilitation	X			• Programs for upgrading employee skills and transition assistance programs • Minimum notice periods regarding operational changes • Post-mining land use • Local communities inclusion in the process
14. Energy consumption		X		• Energy consumption within the organization/country • Energy consumption outside of the organization/country • Energy intensity
15. Climate adaptation and resilience		X		• Financial implications and other risks and opportunities due to climate change

This categorisation provides a structured basis for focusing the analysis on the most widely recognised and discussed impacts of mining activities. The identified impact categories were used to guide the search for relevant indicators in international databases, ensuring that the selected metrics reflect the underlying social, environmental and governance aspects. The table also highlights that several impact categories span multiple dimensions, illustrating the interconnections between environmental and social issues rather than a strict separation between them.

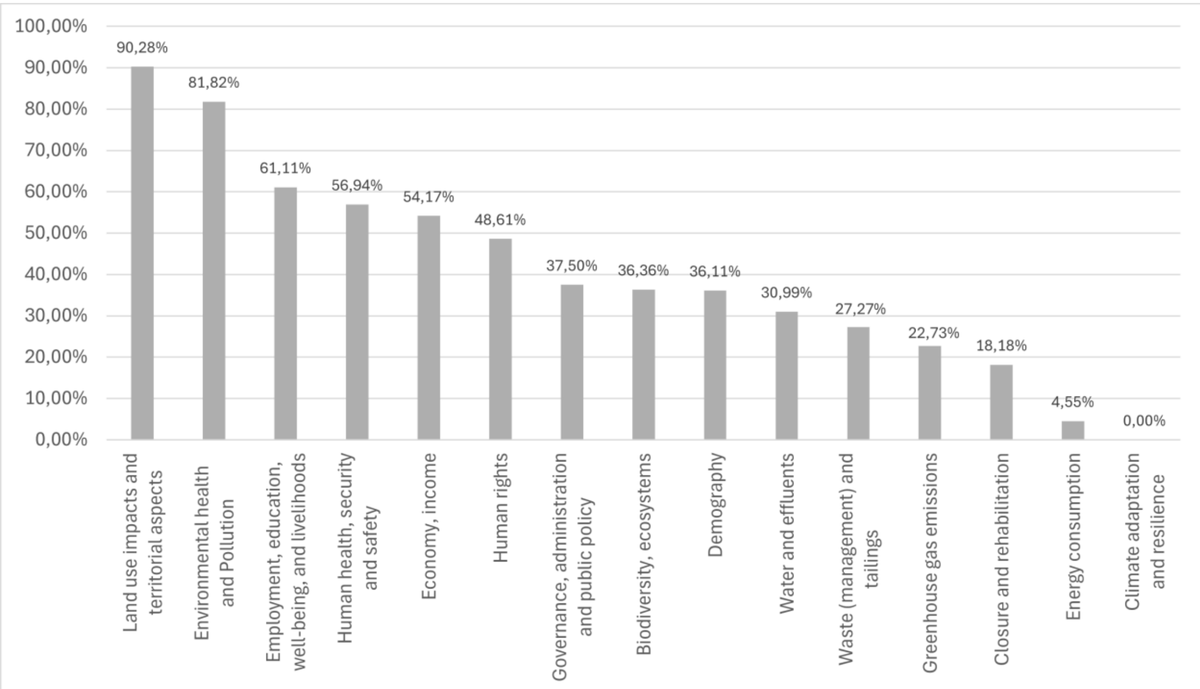

Figure 1. Share of reviewed articles mentioning each impact category

Figure 1 indicates that impacts related to **land use and territorial aspects**, as well as **pollution and ecosystem health**, are among the most frequently discussed topics in the reviewed literature. These are followed by issues related to **well-being and livelihoods**, **human health and safety, income inequality, and human rights**, topics which all appeared in more than 48% of the reviewed papers. While climate change adaptation and resilience are not addressed in the reviewed literature, other topics, including energy consumption, mine closure and rehabilitation, waste generation and greenhouse gas emissions, are also addressed in the literature, but with comparatively lower frequency (less than 40% of occurrence).

5.2 Indicators

A total of 25 indicators were calculated based on data collected from the World Bank Environment, Social and Governance (ESG) database, the OECD Data Explorer and the UNICEF database. Each indicator was selected to reflect, or serve as a proxy for, specific underlying aspects of the impact categories identified through the literature review and presented in Table 2. Not all identified impact aspects could be covered, as suitable and comparable data were not available for some of them.

The results presented in the following sections identify critical raw materials that are predominantly extracted and/or processed in countries facing significant environmental, social or governance issues, as reflected by country-level indicator values. As all indicators are used as proxies and applied at the national level, they capture broader structural conditions in producing and processing countries rather than impacts directly attributable to specific mining or processing activities. Consequently, the results should not be interpreted as evidence of a direct causal relationship between the extraction or processing of a given CRM and the magnitude of the impacts reported, but rather as an indication of elevated contextual risks associated with its supply chain.

For each indicator, the 10 worst-performing critical raw materials are presented for both value-chain stages, based on the calculated indicator scores. Without defining explicit criticality thresholds, this comparative analysis highlights materials that are extracted or processed in countries associated with systematically higher environmental, social and governance pressures. When raw materials were already identified as economically critical for the EU trade market, regardless of the value-chain stage, they are highlighted in bold in the tables.

5.2.1 Environmental impact results for critical raw materials

This subsection presents the results of the environmental indicators calculated for each critical raw material, with a distinction between the extraction stage (Stage 1) and the processing stage (Stage 2). Results are organized by major environmental impact categories identified in the literature, and materials are discussed in terms of their relative performance, with particular attention paid to the worst-performing CRMs for each category.

Net land cover change

Stage 1		Stage 2	
CRM	NLCC (km²)	CRM	NLCC (km²)
Iron ore	-44677,05	**Niobium**	-105132,10
Molybdenum	-30736,34	**Beryllium**	-35804,55
Manganese	-30007,78	**Helium**	-21761,84
Tin	-28013,84	**Borate**	-15853,18
Natural Rubber	-19422,31	**Nickel**	-9236,14
Tantalum	-18091,85	**Cobalt**	-8672,25
Nickel	-16710,02	Molybdenum	-8282,18
Bauxite	-11534,92	Natural cork	-7805,46
Copper	-9532,31	Chromium	-7099,98
Kaolin clay	-9234,13	**Vanadium**	-6116,66
Number of countries with actual data: 241 Global mean used for countries without data: -4088,05 km².			

When examining net changes in natural and semi-natural vegetated land, **iron ore, molybdenum, manganese** and **tin** are associated with the largest losses in their countries of extraction (Stage 1), with losses exceeding 25,000 km². At the processing stage (Stage 2), **niobium** stands out as the material associated with the highest land cover loss, exceeding 100,000 km², followed by **beryllium and helium.**

These results indicate that the extraction and/or processing of these materials predominantly takes place in countries experiencing substantial net losses of natural and semi-natural vegetated land. As this indicator is used as a proxy at the country level, it reflects broader land-use pressures in producing and processing countries and should not be interpreted as evidence of a direct causal link between CRM extraction or processing activities and observed land cover changes.

Among the materials associated with substantial land cover loss in countries of extraction or processing, 9 raw materials are also identified as economically critical: manganese (Stage I), tantalum (Stage I), nickel (Stages I and II), bauxite (Stage I), copper (Stage I), niobium (Stage II), beryllium (Stage II), cobalt (Stage II), and vanadium (Stage II).

Naturel resource depletion

Stage 1		Stage 2	
CRM	NRD (% GNI)	CRM	NRD (% GNI)
Cobalt	23,46	Natural cork	33,09
Tantalum	14,62	**Phosphorus**	11,14
Sapele wood	12,39	**Lithium**	8,01
Natural Teak wood	7,17	Molybdenum	7,38
Cerium	6,67	**Helium**	6,15
Manganese	6,64	**Nickel**	4,98
Lithium	5,45	**Scandium**	4,40
Bauxite	4,73	**Beryllium**	4,01
Titanium	4,43	Chromium	3,72

Zirconium	4,31	**Silicon metal**	3,59
Number of countries with actual data: 218			
Global mean used for countries without data: 4,396 %GNI			

When focusing on **natural resource depletion**, **cobalt** and **tantalum**, that are already critical economically, clearly stand out at the extraction stage (Stage 1), with values substantially higher than those of other materials, indicating a particularly high level of resource depletion relative to national income. They are followed by several materials associated with forestry and biomass resources, as well as by **manganese, lithium, bauxite and titanium**, which also present an economical criticality.

At the processing stage (Stage 2), **natural cork** shows the highest level (> 30% GNI) **of natural resource depletion**, followed by phosphorus and lithium. Other materials such as molybdenum, helium and nickel also appear among the worst performers, although with lower depletion levels. Among the materials associated with high natural resource depletion at Stage 2, phosphorus, lithium, helium, nickel, scandium, beryllium and silicon metal are also identified as economically critical.

This overlap highlights a subset of materials for which economic criticality coincides with particularly high pressures on natural resources.

Tree cover loss

Stage 1		Stage 2	
CRM	TCL (ha)	CRM	TCL (ha)
Cerium	4316824,22	**Niobium**	2871632,99
Iron ore	1693144,69	**Vanadium**	2164007,68
Phosphate rock	1360452,82	**Nickel**	1975920,98
Cobalt	1312748,34	**Aluminium**	1250919,82
Molybdenum	1198037,18	Natural cork	1247857,00
Coking coal	1123176,57	**Beryllium**	1159599,18
Tin	939029,92	**Germanium**	1087892,02
Potash	903420,89	Molybdenum	1032947,39
Tantalum	865417,85	**Helium**	910675,64
Natural graphite	848168,86	**Borate**	839502,28
Number of countries with actual data: 188			
Global mean used for countries without data: 134332,03 ha			

When examining tree cover loss, cerium is associated with by far the highest losses at the extraction stage (Stage 1), with more than 4 millions of hectares of tree cover loss, followed by phosphate rock and **cobalt**, with affected areas exceeding one million hectares. Several other materials, including molybdenum, coking coal and **tantalum**, also appear among the worst performers.

At the processing stage (Stage 2), niobium stands out with the highest tree cover loss, followed by **vanadium** and **nickel**. Other materials such as aluminium, **beryllium**, germanium and **helium** also rank among the top contributors. A number of these materials are simultaneously economically critical, highlighting an overlap between economic importance and pressures on forest cover.

Freshwater use

Stage 1		Stage 2	
CRM	Freshwater use (m³)	CRM	Freshwater use (m³)
Zirconium	431,38	Chromium	400,78
Manganese	330,35	**Manganese**	173,19
Nickel	274,96	**Vanadium**	90,95
Titanium	207,50	Molybdenum	63,00
Fluorspar	139,68	**Phosphorus**	48,14
Chromium	133,73	**Beryllium**	47,66
Phosphate rock	66,40	Natural cork	47,66
Perlite	55,77	**LREEs**	47,55
Iron ore	51,06	**HREEs**	47,55
Molybdenum	48,03	**Magnesium**	47,53
Number of countries with actual data: 24 Global mean used for countries without data: 47,67 m³			

Due to the limited country coverage of this indicator, two additional water-related indicators were calculated, for which data availability across countries was more extensive, to ensure more consistent results.

Level of Water Stress

Stage 1		Stage 2	
CRM	Level of water stress (%)	CRM	Level of water stress (%)
Phosphate rock	55,31	**Helium**	167,22
Baryte	48,25	**Aluminium**	67,16
Strontium	43,25	**Arsenic**	48,36
Borate	42,62	Chromium	45,90
LREEs	41,82	**Bismuth**	45,53
Tin	40,00	Lead	45,32
Fluorspar	39,86	Molybdenum	43,79
HREEs	37,59	Rhenium	43,29
Zirconium	34,60	Iron ore	42,97
Talc	33,50	**Antimony**	42,61
Number of countries with actual data: 176 Global mean used for countries without data: 69,55 %			

Annual freshwater withdrawals

Stage 1		Stage 2	
CRM	Freshwater withdrawals (% renewable freshwater resources)	CRM	Freshwater withdrawals (% renewable freshwater resources)
Talc	59,78	**Helium**	148,23
Phosphate rock	56,51	**Aluminium**	70,23
Silica sand	43,63	Tellurium	54,49
Baryte	40,03	Iron ore	47,18

Tin	35,21	Rhenium	46,79
Hydrogen	34,89	Lead	46,79
Molybdenum	33,48	Molybdenum	45,70
Limestone	30,55	Chromium	40,95
Lead	28,88	**Phosphorus**	36,28
Aggregates	28,33	Cadmium	36,14
Number of countries with actual data: 220 Global mean used for countries without data: 107,89 %			

Air pollutant emission

(a) SO_x emissions

Stage 1		Stage 2	
CRM	Sox emissions (kg/1000USD)	CRM	Sox emissions (kg/1000USD)
Lithium	1,192	**Phosphorus**	1,421
Borate	0,777	**Magnesium**	0,538
Zirconium	0,776	**Borate**	0,525
Antimony	0,691	Tellurium	0,514
Cerium	0,652	Natural cork	0,510
Tantalum	0,527	**LREEs**	0,505
Zinc	0,519	**HREEs**	0,505
Sapele wood	0,510	**Beryllium**	0,481
Natural Teak wood	0,505	**Niobium**	0,472
Manganese	0,503	Chromium	0,459
Number of countries with actual data: 58 Global mean used for countries without data: 0,51 kg/1000USD			

(b) NO_x emissions

Stage 1		Stage 2	
CRM	Nox emissions (kg/1000USD)	CRM	Nox emissions (kg/1000USD)
Lithium	1,219	**Phosphorus**	1,219
Zirconium	0,671	**Beryllium**	0,671
Cerium	0,620	**Aluminium**	0,620
Coking coal	0,558	**Nickel**	0,558
Zinc	0,475	Molybdenum	0,475
Silver	0,472	**Magnesium**	0,472
Titanium	0,447	Natural cork	0,447
Fluorspar	0,441	**HREEs**	0,441
Lead	0,404	**LREEs**	0,404
Phosphate rock	0,389	Chromium	0,389
Number of countries with actual data: 59 Global mean used for countries without data: 0,37 kg/1000USD			

GHG emissions

Stage 1		Stage 2	
CRM	GHG emissions ($kCO_2eq/1000USD$)	CRM	GHG emissions ($kCO_2eq/1000USD$)
Cerium	0,577	**LREEs**	0,508
LREEs	0,489	**HREEs**	0,505
HREEs	0,432	**Magnesium**	0,500
Zirconium	0,426	**Phosphorus**	0,483
Natural graphite	0,400	Chromium	0,388
Manganese	0,390	**Niobium**	0,366
Phosphate rock	0,358	**Vanadium**	0,348
Baryte	0,352	Molybdenum	0,340
Nickel	0,319	**Beryllium**	0,332
Titanium	0,314	Tellurium	0,330
Number of countries with actual data: 89 Global mean used for countries without data: 0,253 $kCO_2eq/1000USD$			

Waste generation

Stage 1		Stage 2	
CRM	Waste generated (tons)	CRM	Waste generated (tons)
Lithium	539124,03	**Tellurium**	76232,91
Zirconium	221289,48	**Nickel**	61726,74
Coking coal	178743,75	**Germanium**	57392,26
Zinc	136629,22	Rhenium	57085,98
Titanium	96476,66	**Cobalt**	55583,65
Lead	91071,70	Chromium	47798,40
Chromium	72624,83	Sulphur	37312,21
Iron ore	69714,47	**Copper**	36899,17
Manganese	51515,68	**Helium**	36448,85
Talc	49282,54	**Phosphorus**	35752,12
Number of countries with actual data: 40 Global mean used for countries without data: 35398,14 tons			

5.2.2 Social impact results for critical raw materials

This subsection presents the results of the social indicators, again distinguishing between Stage 1 and Stage 2. Results are discussed by thematic dimensions reflecting key social risks identified in the literature, with a focus on materials exhibiting comparatively high social impacts.

Child labour

Stage 1		Stage 2	
CRM	Child labour (% of child population)	CRM	Child labour (% of child population)
Coking coal	11,19	Molybdenum	15,14
Phosphate rock	11,19	**Borate**	11,08
Aggregates	11,08	Chromium	11,08
Kaolin clay	11,08	Indium	11,08
Manganese	11,08	**Magnesium**	11,08
Potash	11,08	**Phosphorus**	11,08
Tantalum	11,08	Tin	11,08
Zinc	11,08	**Aluminium**	10,97
Baryte	10,97	**Arsenic**	10,97
Bauxite	10,97	**Beryllium**	10,97
Number of countries with actual data: 93 Global mean used for countries without data: 10,97 % of child population			

Gini index

Stage 1		Stage 2	
CRM	Gini index (-)	CRM	Gini index (-)
Borate	44,034	Molybdenum	51,491
Antimony	42,587	**Niobium**	48,071
Tantalum	41,644	Natural cork	44,700
Sapele wood	40,799	**Borate**	43,645
Molybdenum	39,593	**Lithium**	41,603
Manganese	39,129	**Beryllium**	36,982
Silver	38,582	**Helium**	36,281
Tin	38,136	**Magnesium**	35,967
Iron ore	37,884	**LREEs**	35,667
Natural graphite	36,913	**HREEs**	35,663
Number of countries with actual data: 126 Global mean used for countries without data: 35,28			

Economic and social rights performance score

Stage 1		Stage 2	
CRM	ESR performance score (-)	CRM	ESR performance score (index)
Cobalt	1,8541	Natural cork	2,1080
Bauxite	1,8926	Chromium	2,1983
Sapele wood	1,9379	**Manganese**	2,2867
Manganese	2,0866	**Helium**	2,2881
Natural Teak wood	2,0935	**Cobalt**	2,2980
Natural Rubber	2,1022	**Niobium**	2,3035
Zirconium	2,1170	Tellurium	2,3316
Tantalum	2,1318	**Vanadium**	2,3322
Tungsten	2,1834	**Nickel**	2,3445
Fluorspar	2,2458	**Aluminium**	2,3460
Number of countries with actual data: 182 Global mean used for countries without data: 2,2047			

Mortality, Morbidity and Welfare Cost from Environmental Risks

This indicator is composed of six sub-indicators, for which the results are presented below.

1. Exposure to ambient $PM_{2.5}$

Stage 1		Stage 2	
CRM	DALY (from $PM_{2,5}$)	CRM	DALY (from $PM_{2,5}$)
LREEs	21,88	**LREEs**	22,75
HREEs	17,98	**HREEs**	22,63
Baryte	17,91	**Magnesium**	22,27
Natural graphite	15,45	Rhenium	16,05
Sapele wood	15,10	**Phosphorus**	14,59
Cerium	13,98	**Bismuth**	14,35
Phosphate rock	13,23	Tellurium	13,50
Borate	12,74	**Antimony**	12,93
Manganese	12,66	Cadmium	12,87
Natural Teak wood	12,58	Molybdenum	12,27
Number of countries with actual data: 212 Global mean used for countries without data: 10,40 DALY			

2. Exposure to lead

Stage 1		Stage 2	
CRM	DALY (from lead)	CRM	DALY (from lead)
LREEs	3,76	**LREEs**	3,91
HREEs	2,92	**HREEs**	3,89
Baryte	2,92	**Magnesium**	3,78
Natural graphite	2,61	**Bismuth**	2,81
Natural Teak wood	2,04	**Antimony**	2,46

Natural cork	1,96	**Arsenic**	2,38
Phosphate rock	1,94	Rhenium	1,74
Fluorspar	1,93	**Phosphorus**	1,71
Cerium	1,80	Cadmium	1,67
Bentonite	1,75	**Gallium**	1,62
Number of countries with actual data: 212 Global mean used for countries without data: 1,69 DALY			

3. Exposure to occupational carcinogens

Stage 1		Stage 2	
CRM	DALY (from carcinogens)	CRM	DALY (from carcinogens)
Silica sand	4,40	**Scandium**	4,76
Hydrogen	4,19	**Hafnium**	4,40
Diatomite	3,61	Indium	4,10
Aggregates	3,34	**Arsenic**	3,77
Talc	3,17	Cadmium	3,57
Limestone	3,09	Silver	3,49
Lithium	3,04	**Fluorspar**	3,38
Feldspar	3,03	**Coking coal**	3,28
Gypsum	3,02	**Gallium**	3,28
Potash	2,94	Zinc	3,20
Number of countries with actual data: 212 Global mean used for countries without data: 1,06 DALY			

4. Exposure to occupational PM gases fumes

Stage 1		Stage 2	
CRM	DALY (from PM, gas, fumes)	CRM	DALY (from PM, gas, fumes)
LREEs	2,70	**LREEs**	2,82
HREEs	2,21	**HREEs**	2,80
Natural graphite	1,76	**Magnesium**	2,70
Baryte	1,55	**Bismuth**	1,88
Natural Teak wood	1,44	**Phosphorus**	1,72
Tin	1,29	**Antimony**	1,64
Cerium	1,29	**Gallium**	1,60
Borate	1,21	**Arsenic**	1,54
Bentonite	1,07	**Beryllium**	1,48
Molybdenum	1,05	**Borate**	1,30
Number of countries with actual data: 212 Global mean used for countries without data: 0,76 DALY			

5. Exposure to unsafe water source :

Stage 1	Stage 2

CRM	DALY (from unsafe water)	CRM	DALY (from unsafe water)
Sapele wood	32,18	Natural cork	23,48
Tantalum	20,11	Chromium	5,74
Bauxite	19,41	Tellurium	4,04
Cobalt	16,60	**Cobalt**	3,59
Natural Rubber	8,64	**Manganese**	3,50
Natural Teak wood	8,24	**Aluminium**	3,02
Zirconium	7,53	Molybdenum	2,97
Manganese	4,99	**Nickel**	2,83
Titanium	4,87	Iron ore	2,69
Phosphate rock	3,47	Lead	2,44
Number of countries with actual data: 212 Global mean used for countries without data: 8,47 DALY			

6. Exposure to occupational noise

Stage 1		Stage 2	
CRM	DALY (from noise)	CRM	DALY (from noise)
LREEs	1,55	**LREEs**	1,61
HREEs	1,33	**HREEs**	1,60
Natural graphite	1,15	**Magnesium**	1,55
Natural Rubber	0,99	**Bismuth**	0,96
Baryte	0,95	**Phosphorus**	0,96
Cerium	0,95	Molybdenum	0,94
Natural Teak wood	0,94	**Antimony**	0,88
Silver	0,75	**Niobium**	0,85
Fluorspar	0,74	**Beryllium**	0,79
Tantalum	0,72	**Gallium**	0,78
Number of countries with actual data: 212 Global mean used for countries without data: 0,67 DALY			

5.2.3 Governance impact results for critical raw materials

This subsection presents results for the six Worldwide Governance Indicators, reflecting governance quality in countries involved in the extraction and processing of CRMs. Results are discussed by governance dimension, with emphasis on materials consistently associated with weaker governance conditions.

World governance indicators

This indicator is composed of six sub-indicators, for which the results are presented below.

1. Voice and Accountability.

Stage 1		Stage 2	
CRM	Estimate (-)	CRM	Estimate (-)
LREEs	-1,5014	**LREEs**	-1,6237

Natural Teak wood	-1,4871	**HREEs**	-1,6079
Cerium	-1,2411	**Magnesium**	-1,5298
Sapele wood	-1,1019	Natural cork	-1,2136
Borate	-1,0689	**Phosphorus**	-0,9278
HREEs	-0,9343	**Borate**	-0,3560
Antimony	-0,7606	**Helium**	-0,1529
Cobalt	-0,7596	**Bismuth**	-0,0916
Natural graphite	-0,7483	Tellurium	-0,0247
Baryte	-0,7368	**Antimony**	0,0065
Number of countries with actual data: 210 Global mean used for countries without data: -0,0730			

2. Political Stability and Absence of Violence.

Stage 1		Stage 2	
CRM	Estimate (-)	CRM	Estimate (-)
Natural Teak wood	-1,4555	Natural cork	-2,1192
Cobalt	-1,4276	**Borate**	-0,6354
Tantalum	-1,1727	**Niobium**	-0,3621
Sapele wood	-1,1461	**Hafnium**	-0,2226
Borate	-0,9530	**Phosphorus**	-0,2133
Bauxite	-0,7422	Chromium	-0,1928
Antimony	-0,6831	**Magnesium**	-0,1705
Cerium	-0,5797	**LREEs**	-0,1492
Phosphate rock	-0,5158	**HREEs**	-0,1476
Natural Rubber	-0,4758	Molybdenum	-0,1181
Number of countries with actual data: 215 Global mean used for countries without data: 0,0071			

3. Government Effectiveness.

Stage 1		Stage 2	
CRM	Index (-)	CRM	Index (-)
Cobalt	-0,9958	Natural cork	-1,6934
Natural Teak wood	-0,9837	**Niobium**	0,0501
Sapele wood	-0,7808	Tellurium	0,1502
Tantalum	-0,6410	**Phosphorus**	0,1705
Bauxite	-0,6142	Chromium	0,3242
Manganese	-0,2226	**Borate**	0,4334
Antimony	-0,1169	Rhenium	0,5258
Borate	-0,0675	**Nickel**	0,6086
Natural Rubber	0,1367	**Aluminium**	0,6327
Cerium	0,1415	**Manganese**	0,6741
Number of countries with actual data: 213 Global mean used for countries without data: 0,0758			

4. Regulatory Quality

Stage 1		Stage 2	
CRM	Estimate (-)	CRM	Estimate (-)
Natural Teak wood	-0,9162	Natural cork	-1,2848
Cobalt	-0,7887	**Niobium**	-0,0582
Sapele wood	-0,7211	**LREEs**	-0,0555
Bauxite	-0,6135	**HREEs**	-0,0548
Cerium	-0,5850	**Magnesium**	-0,0229
Tantalum	-0,5183	**Phosphorus**	-0,0210
Antimony	-0,3148	Tellurium	0,0824
Manganese	-0,2221	**Borate**	0,3320
Borate	-0,2094	Chromium	0,3498
Natural graphite	-0,0699	**Vanadium**	0,3665
Number of countries with actual data: 213 Global mean used for countries without data: 0,0002			

5. Rule of Law

Stage 1		Stage 2	
CRM	Estimate (-)	CRM	Estimate (-)
Natural Teak wood	-1,2649	Natural cork	-1,6266
Sapele wood	-1,0939	**LREEs**	-0,5608
Cobalt	-1,0291	**HREEs**	-0,5551
Borate	-0,8291	**Magnesium**	-0,5170
Bauxite	-0,8096	**Phosphorus**	-0,3798
Tantalum	-0,7864	**Borate**	-0,1920
Cerium	-0,7845	**Niobium**	-0,1767
Antimony	-0,7713	Tellurium	-0,0836
LREEs	-0,5010	**Helium**	0,2580
Manganese	-0,3832	**Bismuth**	0,3285
Number of countries with actual data: 215 Global mean used for countries without data: -0,0075			

6. Control of Corruption.

Stage 1		Stage 2	
CRM	Estimate (-)	CRM	Estimate (-)
Sapele wood	-1,0909	Natural cork	-1,5153
Natural Teak wood	-0,9231	**Niobium**	-0,1203
Cobalt	-0,9150	**Phosphorus**	-0,0848
Bauxite	-0,8036	**Tellurium**	0,0193
Borate	-0,5552	**Borate**	0,0275
Tantalum	-0,5408	**HREEs**	0,1021
Antimony	-0,5241	**LREEs**	0,1029
Cerium	-0,4295	**Magnesium**	0,1097
Manganese	-0,4002	Chromium	0,3297
Natural Rubber	-0,3217	**Vanadium**	0,3921

Number of countries with actual data: 215
Global mean used for countries without data: 0,0046

A synthesis of all CRMs appearing among the top ten worst performers across the 25 indicators is presented in Table 3, together with the number of indicators for which each material ranks among the worst performers at each value-chain stage. Materials identified as economically critical are highlighted in bold. CRMs for which the combined Stage 1 and Stage 2 score is greater than or equal to 10 are highlighted in red.

Table 3. Number of occurrence of each CRM in the top ten worse performers of the 25 indicators, across stages 1 and 2.

CRM	Stage 1	Stage 2	CRM	Stage 1	Stage 2	CRM	Stage 1	Stage 2
Aggregates	3	0	**Germanium**	0	2	**Phosphate rock**	8	3
Aluminium	0	8	**Helium**	1	8	**Phosphorus**	0	13
Antimony	8	6	**HREEs**	6	9	Potash	4	0
Arsenic	0	5	Hydrogen	2	0	Rhenium	0	6
Baryte	9	0	Iron ore	5	3	Sapele wood	9	0
Bauxite	10	0	Kaolin clay	2	0	**Scandium**	0	2
Bentonite	2	0	Lead	3	4	Silica sand	2	0
Beryllium	0	11	Limestone	2	0	Silver	3	1
Bismuth	0	7	**Lithium**	5	2	**Silicon metal**	0	1
Borate	11	12	**LREEs**	6	8	**Strontium**	1	0
Cadmium	0	4	**Magnesium**	0	12	Sulphur	0	1
Cerium	15	0	**Manganese**	8	5	Talc	4	0
Chromium	2	16	Molybdenum	7	11	**Tantalum**	14	0
Cobalt	10	4	Natural cork	1	14	Tellurium	0	12
Coking coal	4	1	**Natural graphite**	7	1	Tin	6	1
Copper	1	1	Natural Rubber	6	3	**Titanium**	6	0
Diatomite	1	0	Natural Teak wood	9	0	**Tungsten**	1	0
Feldspar	1	0	**Nickel**	3	6	**Vanadium**	0	7
Fluorspar	6	1	**Niobium**	0	9	Zinc	4	1
Gallium	0	6	Perlite	1	0	Zirconium	9	0

5.3 Cross-cutting comparison of critical raw materials across impact dimensions

This subsection synthesizes results across environmental, social and governance dimensions to identify critical raw materials that consistently appear among the worst performers across multiple impact categories, as well as those that rank poorly in impact categories that are particularly prominent in the scientific literature.

On one hand, by associating the calculated indicators with the impact categories identified in the literature, and by taking into account the relative prominence of these categories in the scientific literature, indicators can be prioritised according to their relevance. On the other hand, for each indicator, the worst-performing critical raw materials were identified based on their relative ranking. This combined approaches allow for an assessment of which indicators point to the most significant impacts, and of the CRMs most closely associated with these high-priority issues.

Considering the impact categories addressed in more than 50% of the reviewed articles, namely land use and territorial aspects; environmental health and pollution; employment, education, well-being and livelihoods; human health, security and safety; and economy, income and inequality – the most relevant indicators for assessing these impacts can be identified based on Table 3. These indicators include: (1) net land cover change; (2) natural resource depletion, which also captures pressures on biodiversity and ecosystems; (3) tree cover loss, also reflecting biodiversity and ecosystem impacts; (4) SO_x and NO_x emissions; (5) child labour; (6) the Gini index; (7) the economic and social rights performance score; and (8) mortality, morbidity and welfare costs from environmental risks.

Focusing on critical raw materials identified as economically critical for the EU and on the results of these 8 prioritised indicators, Table 6 shows that, among the 35[1] (economically) critical raw materials identified for the EU in 2023, 32 are associated, through their extraction or processing stages, with significant environmental and/or social impacts (i.e. impacts that have been prioritized). These 32 CRMs are presented in Table 4 and for each material, the supply-chain stage acting as a bottleneck for economic criticality is indicated in parentheses.

This synthesis (Table 4) is based exclusively on indicators prioritised through the literature review. A broader assessment considering the full set of calculated indicators would allow for a more comprehensive mapping of environmental and social impacts across all raw materials, as detailed in the results tables presented in Section 5.2.

Table 4. List of Critical Raw Materials (CRMs) for the EU associated with embedded social and/or environmental issues along their supply chains (top-ten worse-performers)

Aluminium (I)	Coking coal (I)	HREEs (II)	Phosphate rock (I)
Antimony (I)	Copper (I)	Lithium (II)	Phosphorus (II)
Arsenic (II)	Feldspar (I)	LREEs (II)	Scandium (II)
Baryte (I)	Fluorspar (I)	Magnesium (II)	Silicon metal (II)
Bauxite (I)	Gallium (II)	Manganese (II)	Tantalum (I)
Beryllium (I)	Germanium (II)	Natural graphite (I)	Titanium (II)
Bismuth (II)	Hafnium (II)	Nickel (II)	Tungsten (II)
Borate (I)	Helium (II)	Niobium (I)	Vanadium (I)

Within this group, certain CRMs emerge as being associated with particularly high environmental and social pressures along their supply chains. Heavy rare earth elements (HREEs) and light rare earth elements (LREEs) stand out, each appearing 11 times among the top ten worst performers across the prioritised socio-environmental indicators and across both value-chain stages. They are followed by borate and manganese, with 10 occurrences; beryllium and tantalum, with 9 occurrences; and magnesium and phosphorus, with 8 occurrences. These results highlight a subset of materials whose economic criticality coincides with recurrent poor performance

In addition, some materials that are not identified as economically critical are nevertheless associated, through their supply chains and the countries in which extraction and processing take place, with a high number of environmental and social impacts. This is notably the case for molybdenum, which appears 12 times among the top ten worst performers, for the prioritized impact indicators, across

[1] With aluminium and bauxite considered as distinct materials

both stages, as well as for natural cork, with 9 occurrences, and cerium, with 8 occurrences. These findings indicate that elevated environmental and social pressures are not exclusively associated with materials classified as economically critical. This is clearly illustrated in Table 6, which shows, for each CRM, its economic criticality alongside the prioritised socio-environmental impacts associated with its supply chain, indicating the value-chain stage concerned. An “I” denotes poor performance at the extraction stage (Stage I), while an “II” indicates poor performance at the processing stage (Stage II).

Table 5. Correspondence between impact categories and indicators

	Envrionmental indicators										Social indicators				Governance indicators
	Net land cover change	Natural resource depletion	Tree cover loss	Freshwater use	Level of water stress	Annual freshwater withdrawals	SOx emissions	Nox emissions	Greenhous gas emissions	Mining waste generation	Child labour	Gini Index	Economic and social rights performance score	Mortality, morbidity and welfare cost from environmental risks	Wolrd Governance Indicators
Land use impacts and territorial aspects	**X**	**X**	**X**												
Environmental health and pollution							**X**	**X**							
Employment, education, well-being and livelihoods											**X**		**X**		
Human health, security and safety														**X**	
Economy, income and inequality												**X**			
Human rights													X		
Governance, administration and public policy															X
Biodiversity and ecosystems		X	X												
Demography															
Water and effluents				X	X	X									
Waste (management) and tailings										X					
Greenhouse gas emissions									X						
Closure and rehabilitation															
Energy consumption															
Climate adaptation and resilience															

Table 6 provides a detailed overview of the environmental and social impacts associated with each CRM identified among the top ten worst performers. Unlike Table 3, which presents a quantitative synthesis of the total number of occurrences of each CRM across the full set of 25 indicators and both value-chain stages, Table 6 focuses specifically on the subset of prioritised socio-environmental indicators identified through the literature review.

While Table 3 offers a comparative ranking by counting how frequently each material appears among the worst performers, Table 6 specifies the exact nature of the impacts involved and indicates the value-chain stage at which these impacts occur (Stage I: extraction; Stage II: processing). It therefore provides a more qualitative and impact-specific perspective, highlighting the types of environmental and social pressures embedded in the supply chains of each material.

As a result, differences in the total number of occurrences between Tables 3 and 6 reflect their distinct analytical scopes: the former is based on the complete set of calculated indicators, whereas the latter is restricted to prioritised indicators considered most prominent in the scientific literature. The CRMs highlighted in purple correspond to those with a combined Stage I and Stage II socio-environmental impact score equal to or exceeding 7.

Table 6. List of CRMs (top-ten worse-performers) and their environmental and social associated impacts.

Top 10 CRMs	Economical criticality	Net land use cover change	Natural resource depletion	Tree cover loss	SOx emissions	NOx emissions	Child labour	Gini index	Economic and social right performance score	PM2.5 exposure	Lead exposure	Occupational carcinogens	PM gases fumes	Unsafe water	Occupational noise	Nb of socio-env. impacts embedded in stage I	Nb of socio-env. impacts embedded in stage II
Aggregates							I					I				2	0
Aluminium	I			II		II	II		II					II		0	5
Antimony	I				I			I		II	II		II		II	2	4
Arsenic	II						II				II	II	II			0	4
Baryte	I						I			I	I		I		I	5	0
Bauxite	I	I	I				I		I					I		5	0
Bentonite											I		I			2	0
Beryllium	I	II	II	II	II	II	II	II					II		II	0	9
Bismuth	II									II	II		II		II	0	4
Borate	I	II		II	I/II		II	I/II		I			I/II			4	6
Cadmium										II	II	II				0	3
Cerium			I	I	I	I				I	I		I		I	8	0
Chromium		II	II		II	II	II		II					II		0	7
Cobalt		II	I	I					I/II					I/II		4	3
Coking coal	I			I		I	I					II				3	1
Copper	I	I														1	0
Diatomite												I				1	0
Feldspar	I											I				1	0
Fluorspar	I					I			I		I	II			I	4	1
Gallium	II										II	II	II		II	0	4
Germanium	II			II												0	1
Gypsum												I				1	0
Hafnium	II											II				0	1
Helium	II	II	II	II				II	II							0	5
HREEs	II				II	II		II		I/II	I/II		I/II		I/II	4	7
Hydrogen												I				1	0
Indium							II					II				0	2
Iron ore		I		I				I						II		3	1
Kaolin clay		I					I									2	0
Lead						I								II		1	1
Limestone												I				1	0
Lithium	II		I/II		I	I		II				I				4	2
LREEs	II				II	II		II		I/II	I/II		I/II		I/II	4	7
Magnesium	II				II	II	II	II		II	II		II		II	0	8
Manganese	I	I	I		I		I	I	I/II	I				I/II		8	2
Molybdenum		I/II	II	I/II		II	II	I/II					I	II	II	4	8
Natural cork		II	II	II	II	II		II	II		I			II		1	8
Natural graphite	I			I				I		I	I		I		I	6	0

Natural Rubber		I							I					I	I	4	0
Natural Teak wood			I		I				I		I		I	I	I	7	0
Nickel	II	I/II	II	II		II			II					II		1	6
Niobium	I	II		II	II			II	II						II	0	6
Phosphate rock	I			I		I	I			I	I			I		6	0
Phosphorus	II		II		II	II	II			II	II		II		II	0	8
Potash				I			I					I				3	0
Rhenium										II	II					0	2
Sapele wood			I		I			I	I	I				I		6	0
Scandium	II		II									II				0	2
Silica sand												I				1	0
Silicon metal	II		II													0	1
Silver						I		I				II			I	3	1
Talc												I				1	0
Tantalum	I	I	I	I	I		I	I	I					I	I	9	0
Tellurium					II				II	II				II		0	4
Tin		I		I			II	I					I			4	1
Titanium	II		I			I								I		3	0
Tungsten	II								I							1	0
Vanadium	I	II		II					II							0	3
Zinc					I	I	I					II				3	1
Zirconium			I		I	I			I					I		5	0

6. CONCLUSION

The objectives of this task were threefold. First, it aimed to identify the environmental, social and governance impact categories most frequently discussed in the scientific literature as being associated with mining activities. Second, it sought to select and calculate a set of indicators capable of estimating these impacts at the country level, reflecting the social, ethical and environmental conditions under which critical raw materials are extracted and processed in the countries contributing to European supply chains. Third, based on the results of these indicators, the analysis aimed to identify, among the raw materials already classified as economically critical in Task 3.1 of the CAMBIUM project, those that are additionally associated with significant environmental, social and/or governance challenges along their supply chains, particularly for impact categories identified as prominent in the literature.

Based on a targeted review of the scientific literature specific to the mining sector, social, environmental and governance impacts were structured into 15 broad impact categories. Among these, 5 categories were identified as particularly prominent, as they are discussed in more than 50% of the reviewed articles. These include land use change impacts and territorial aspects; environmental health and pollution management affecting air, soil and water; employment, education, well-being and livelihoods; human health, security and safety; and economy, income and inequality. These categories encompass the impact dimensions most consistently highlighted in the literature as critical in relation to mining activities.

Using these prioritized impact categories as a guiding framework, 25 proxy indicators were identified from international databases and calculated for each raw material. 8 proxy indicators were selected to assess the social and environmental criticality of raw materials and highlight the CRMs most closely linked to major social and environmental concerns throughout their supply chains: net land cover change; natural resource depletion, which also captures pressures on biodiversity and ecosystems; tree cover loss, also reflecting biodiversity and ecosystem impacts; SO_x and NO_x emissions; child labour; the Gini index; the economic and social rights performance score; and mortality, morbidity and welfare costs (measured in Disability-Adjusted Life Year) from environmental risks.

The results of these indicators show that, among the 35 raw materials identified as economically critical for the European market, 32 are associated with significant environmental and/or social impacts along their supply chains. These impacts are linked to the countries in which extraction and processing activities take place and reflect broader environmental, social and governance challenges affecting these supply chains.

Defining explicit criticality thresholds for each indicator was not feasible, as establishing acceptable or unacceptable levels for social and environmental impacts raises sensitive normative and ethical questions. This is particularly the case for indicators related to human health, such as years of life lost or impaired due to exposure to environmental risks. Instead, a relative approach was adopted: for each indicator, the ten worst-performing raw materials were identified based on their relative scores. This approach allows for a transparent comparison across materials without imposing arbitrary thresholds and highlights those raw materials most consistently associated with elevated impacts across high-priority dimensions.

Taken together, these results indicate that economic criticality assessments alone do not adequately capture the environmental, social and governance challenges that are prevalent along raw material supply chains, underscoring the importance of adopting a multidimensional perspective when assessing material criticality.

7. RECOMMANDATIONS

The present analysis highlights several avenues for further methodological development that could strengthen the integration of environmental, social and governance dimensions into raw material criticality assessments.

First, future work could expand the scope of indicators considered, in order to capture a broader range of impact dimensions. In particular, moving from an impact-based perspective to a risk-based perspective could provide a more comprehensive analytical framework. While the present study focuses on indicators reflecting impacts or pressures, risk-based approaches explicitly take into account and combine information on impacts of a hazard with elements of exposure and of vulnerability to assess a risk. Such an approach could allow for a more nuanced assessment of supply chain risks, especially in contexts where similar impacts may have different implications depending on local socio-economic or environmental conditions.

Second, additional work could be undertaken to explore the definition of criticality thresholds for environmental, social and governance indicators. While this study relies on a relative ranking approach based on the identification of the top ten worst-performing CRMs for each indicator, this method has inherent limitations. In particular, it does not allow for an assessment of whether all materials appearing among the worst performers are associated with genuinely problematic indicator values, or whether only a small subset exhibits markedly elevated scores while the remainder performs close to global averages. The use of explicit thresholds would help distinguish between indicators reflecting truly critical situations and those for which observed values remain within acceptable or non-critical ranges. In this context, threshold-based approaches represent a clear methodological improvement over relative rankings.

At present, there are no universally defined normative thresholds indicating when an indicator becomes “critical” from a social or environmental perspective, particularly in the context of raw material supply chains. A targeted literature review could help identify which indicators may lend themselves to threshold-based interpretation and which types of thresholds are most appropriate. Indeed, criticality thresholds within the CAMBIUM framework could be derived from a combination of three complementary approaches, depending on the indicator considered:

- Normative thresholds could be applied to indicators related to fundamental rights, such as child labour, based on international conventions and standards (e.g. ILO frameworks), as is already the case for some standardized indicators such as the Economic and Social Rights Performance Score.
- Institutional thresholds could be applied to indicators for which international institutions define reference categories or value ranges reflecting underlying institutional standards, such as for Gini index or air emissions and pollution, rather than normative or statistical criteria. Implementing this approach would require a targeted review of guidance and classification frameworks developed by institutions such as the EU, OECD, UN or World Bank, in order to identify and benchmark these thresholds and assess their relevance for mining-related impacts.
- Statistical thresholds based on the upper percentiles of global indicator distributions (e.g. the 75th or 90th percentile) could be applied to indicators such as natural resource depletion, freshwater use or waste generation, for which neither institutional nor normative thresholds are available. This approach would provide an alternative to the relative ranking method adopted in this study, which identifies the top ten worst-performing CRMs for each indicator.

Combining these approaches would allow for a more robust and transparent identification of socio-environmental criticality, while remaining consistent with practices used by institutions around the world.

Third, future analyses could place greater emphasis on indicators and datasets that are directly linked to mining and processing activities, rather than relying primarily on country-level proxy indicators. While the use of proxies provides valuable information on the broader environmental, social and governance conditions in countries where critical raw materials are extracted or processed, it does not allow for a direct attribution of impacts to specific mining or processing activities along CRM supply chains. Developing or integrating more mining-specific indicators, such as sector-specific water use, emissions or occupational risks, would help reduce this limitation. An example in this study is the use of mining-specific freshwater use data from the OECD Data Explorer. Expanding this type of sector-specific data collection could improve the precision of future assessments and better reflect the direct impacts associated with raw material extraction and processing.

Fourth, future applications of this methodology could benefit from the systematic inclusion of an indicator representativeness analysis. In this study, differences in country coverage across indicators were documented, notably through the number of countries for which actual data were available. This information is essential for interpreting results, as indicators with limited data coverage rely more heavily on global mean proxy values, which may lead to a convergence of CRM scores around the global average and reduce the discriminatory power of the indicator. Incorporating representativeness metrics into the analysis, such as country coverage or the share of proxy values used for each CRM, could help assess the robustness of indicator results and inform on the relative weighting that should be given to an indicator in the overall assessment. While this would introduce a potential bias in favour of better-documented indicators, it would also increase transparency and improve the interpretation of results by explicitly accounting for data availability constraints.

Together, these recommendations point towards a gradual refinement of the CAMBIUM framework, combining broader risk-based perspectives, more explicit threshold-setting approaches and more activity-specific data. Such developments would further enhance the robustness and policy relevance of multidimensional criticality assessments for raw materials.

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