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Systematic Review

A Systematic Literature Review of Existing Methods and Tools for the Criticality Assessment of Raw Materials: A Focus on the Relations between the Concepts of Criticality and Environmental Sustainability

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Abstract: Critical raw materials have significant economic and social impacts across numerous sectors. Numerous artifacts have been developed to assess their criticality. However, there is no univocity around the factors determining criticality. A systematic literature review was conducted to consider all academic works and official reports on criticality assessment. The review aimed to classify these artifacts to provide a clear picture of the heterogenous literature, with a focus on the relationship between criticality and environmental sustainability. Works proposing or updating criticality assessment artifacts were included according to the eligibility criteria. Academic sources were drawn from the Scopus Database in 2023. Official reports included those considered seminal by academic literature. The risk of bias in the selection and classification of the 162 works was low, as the review sought to be comprehensive. The included artifacts are systematically classified. A mapping of the identified criticality assessment tools and methods has been developed. The review found that while environmental impacts are considered in several works, the theoretical connection between criticality and environmental sustainability is weak. Three perspectives on this relationship are identified and discussed. The main limitation of this study is the inability to analyze undisclosed artifacts. It was conducted under the Horizon Europe Programme (Grant Number 101091490).

Keywords: critical raw materials; criticality assessment; environmental sustainability

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Citation: Perossa, D.; Rosa, P.; Terzi, S. A Systematic Literature Review of Existing Methods and Tools for the Criticality Assessment of Raw Materials: A Focus on the Relations between the Concepts of Criticality and Environmental Sustainability. *Resources* **2024**, *13*, 131. https://doi.org/10.3390/resources13090131

Academic Editor: Benjamin McLellan

Received: 19 August 2024
Revised: 12 September 2024
Accepted: 13 September 2024
Published: 18 September 2024

1. Introduction

In recent years, debates related to raw materials and their criticality have been gaining relevance in the academic, industrial, and political spheres [1–3]. The reasons behind this growing interest are related to the increase in the cruciality of the so-called critical raw materials (CRMs) [4–6]. CRMs are commonly referred to as materials that on the one hand cover a crucial importance in industry and society, but, on the other, present risks associated with their usage, like unavailability, environmental impacts, or social impacts (e.g., [5,7,8]).

These discussions have led to the development of several models, tools, and methodologies to assess the criticality of raw materials. Nonetheless, there is a big heterogeneity not only in how they are shaped and in the mathematical procedures they use, but also in what parameters are considered to evaluate if a material is either critical or not [1].

It is important to notice that differences in terms of the parameters that make a material critical or non-critical stem from a different way of conceiving the concept of criticality under an ontological perspective. Indeed, if in a proposed assessment tool environmental sustainability is considered as a criticality element, this means that this concept is considered as falling within the concept of criticality. Otherwise, environmental sustainability is considered as unrelated to criticality. This heterogeneity comes from a lack of conceptual univocity in how criticality is conceived. Furthermore, different criticality assessment models may be focused on different scopes.

As a consequence, the literature related to the topic is very heterogenous and diverse. Thus, it is difficult for academicians and practitioners approaching the topic to orient themselves. Therefore, in this paper, the following research objective is proposed: the mapping of the existing criticality assessment models and tools, providing a snapshot of the current state of the art of this knowledge domain. This will provide a mapping supporting academicians, practitioners, and other interested parties in orienting themselves in this domain.

To achieve this research objective, the following research question is proposed: what is the current state of the art of the material criticality assessment?

Focusing on the rationale of this study, in comparison to previous literature reviews on the topic, this is the most extensive and complete in terms of the considered tools and methods. A relevant example of an extensive literature review on the same knowledge domain is [1]. Nonetheless, in this work, different dimensions of analysis are considered. A major focus is indeed given to the analysis of the parameters that are considered as influencing the criticality of a material in different methodologies. A further difference is the more inclusive scope of this review; here, 108 different methodologies and tools were analyzed. Additionally, Ref. [1] was published a few years ago, and further works have been added to the literature since then. Furthermore, in this work more focus is given to how the methodologies and tools are shaped, and how this influences the support they can provide. Finally, in this review, as a further rationale, particular attention is paid to the connection between the concepts of material criticality and environmental sustainability. The connection between the two is evaluated, both at a methodological and ontological level. An analysis of the attention that different methodologies give to circular economy aspects, and how they are related to criticality and environmental sustainability, is also performed. Other studies related to this connection were carried out in [9,10]. Nonetheless, in those cases, the focus was on methodological integration between a life-cycle assessment (LCA) and a criticality assessment. In this work, the scope is larger, and relationships between environmental sustainability and criticality are analyzed with a more comprehensive perspective. As such, a further objective of the paper is the analysis of the existing relationships between environmental sustainability and criticality. Therefore, a second research question is proposed: what are the relationships between the concepts of environmental sustainability and criticality?

The mentioned research objective and research questions lend themselves well to a review approach, since it is possible to infer what the relationships between criticality and environmental sustainability are from the existing body of knowledge. Furthermore, a review of the existing related literature is the best method to define the current state of the art of material criticality assessment.

Throughout the paper, the following nomenclature will be used:

- Criticality dimensions (CDs): elements whose values are regarded as directly influencing the value of criticality (e.g., higher unavailability risk contributes to a higher criticality).
- Criticality sub-dimensions: elements that are considered as directly impacting on the value of a CD, but that are themselves composed of other parameters (e.g., higher risks that mining activities of a certain material will be closed due to its environmental impacts increases the unavailability risk of that material).
- Parameters: elements that are considered as directly influencing the value of CDs or criticality sub-dimensions, and that are not stem from computation or the combination of further elements (e.g., higher values for the environmental impacts stemming from mining activities increase the risk that these mining activities will be stopped).

The remainder of the paper is structured as follows: in Section 2, the exploited research methodology is presented. In Section 3, the results of the SLR are presented, and in Section 4, they are discussed. Finally, in Section 5, the main conclusions and suggestions for future works are detailed.

2. Materials and Methods

A preliminary narrative search exploiting snowball effect approach was performed [11]. Its aim was to better define the scope of the research and to identify the keywords to be used in the systematic search. Then, a systematic literature review (SLR) [12] was performed. This approach was selected to ensure the maximum possible coverage of documents related to CRMs assessment. The systematic search was conducted on Scopus, which is typically considered the best database for systematic searches, as it provides a better coverage for STEM disciplines compared to alternatives [13]. Here, the research string used is shown below:

TITLE(“Critical Raw Material?” OR “Strategic raw material?” OR “strategic mineral?” OR “Scarce Metal?” OR “Critical Metal?” OR “Critical Mineral?” OR “Scarce Mineral?” OR “Supply Risk?” OR “Material? Security” OR “Geological Survey” OR “critical material?” OR “strategic material?” OR “material criticality” OR “criticality of raw material?” OR “Criticality of Scarce material?” OR “Criticality of Strategic material?” OR “criticality of scarce mineral?” OR “criticality of strategic mineral?” OR “raw material? for emerging technolog*” OR “Strategic material? for emerging technolog*” OR “scarce material? for emerging technolog*” OR “scarce metal? for emerging technolog*” OR “material? criticality” OR “metal? criticality” OR “resource? criticality” OR “resource? efficiency” OR (“criticality” AND (“raw material?” OR “Metal?” OR “Mineral?”)) OR “Critical resource?” OR “criticality of resource?” OR (“Risk?” AND (“raw material?” OR “Metal?” OR “Mineral?”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (EXCLUDE (SUBJAREA, “ARTS”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”)) OR TITLE (“critical component?” OR “strategic component?” OR “scarce component?”) OR TITLE-ABS-KEY (“critical raw material?” AND (“assessment” OR “rating” OR “estimation” OR “analysis” OR “evaluation” OR ”assess” OR ”rate” OR “estimate” OR “analyse” OR “analyze” OR “evaluate”)) OR TITLE (“constrained resource”) OR TITLE (“critical resource use” OR “critical metal resources”) OR TITLE-ABS-KEY (“supply risk” AND “geopolitical”) OR TITLE (“resource criticality”).

Scopus focuses exclusively on academic literature. Thus, to ensure an adequate coverage of all relevant official non-academic documents, a second narrative search was conducted. Thus, the literature reviews found in the systematic search were analyzed, looking in their results for relevant documents that had not previously been found. This process is portrayed in Figure 1.

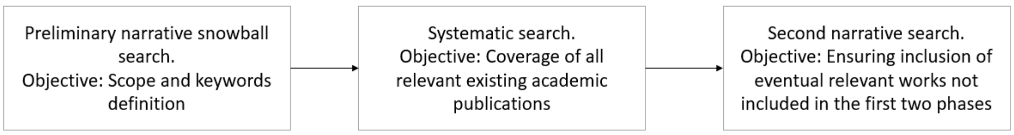

Figure 1. Scheme of the adopted literature search methodology, including a preparatory narrative search, the systematic search, and a second narrative search to include relevant artifacts contained in reports missed out by the previous two searches.

We conducted a systematic review following PRISMA guidelines. The employed protocol is the one proposed in [14]. The documents were analyzed to evaluate their relevance for the work, in two steps: first, it was considered whether the documents were consistent with the scope of the work, i.e., if they were related to the criticality of raw materials and components. Duplicates from the preliminary narrative search were discarded. In the search, filters limiting the search to English language were used, as well as limiting the typology of the document to journal papers and book chapters. The filters related to the typology of documents were chosen to ensure the quality of the uncovered works.

As a second step, it was evaluated whether the documents were proposing a new criticality assessment tool or methodology, or if they were improving or adapting an existing one. All scenario analyses, purely theoretical works, works quantifying sheer supply risk, and sheer assessment methods or tool application cases were discarded. These eligibility criteria were selected, since the review was focused on the criticality assessment domain. Thus, only methodologies performing proper criticality assessments were reviewed. All the authors were involved in the screening process, keeping in constant contact with each other. Each work was analyzed independently by each author. In this way, the risk of bias was limited. Furthermore, the works were all peer-reviewed, and thus their content was written in a clear and understandable manner, further limiting the risk of bias.

Then, the second narrative search was conducted. It led to finding more documents that had been overlooked by the systematic search, as they were all non-academic. Non-academic works were included, since, from what had emerged from the preliminary narrative searches, some of them are seminal for the scope of this work and are often cited.

The criticality assessment artifacts were reviewed in a systematic way, according to the following analysis dimensions:

- Source of the work.
- Year of publication and eventual year of update of the tool or methodology.
- Typology of document (e.g., journal paper, book chapter, or official report).
- Criticality scope: the space the analyzed artifact was conceived to be applied in. Four main scopes are identified, namely (i) global level, assessing criticality of CRMs for the entire world; (ii) country level, assessing criticality for a given country or region; (iii) company level, assessing criticality for a single company; and (iv) product level, assessing the criticality of the materials used for a specific product and thus indirectly assessing the criticality of that product. Here, it was also considered whether the analyzed artifacts were conceived for a specific industry or sector.
- Considered criticality dimensions: this analysis dimension refers to CDs considered by the artifact for the criticality quantification. This is also relevant from a theoretical angle. Indeed, the CDs depend on the idea of criticality that has been, often implicitly, adopted for building the artifact.
- Artifact output: this analysis dimension refers to the shape of the final output of artifact application (e.g., a synthetic criticality indicator, a set of multi-metric indicators, or a two- or three-axes diagram).
- Criticality criteria: this analysis dimension refers to the criteria adopted by the artifacts to define if a material is either critical or non-critical.
- The consideration of environmental impacts: this analysis dimension refers to the inclusion of the environmental impacts and of the concept of environmental sustainability in the criticality assessment. Furthermore, the terms and modalities in which environmental impacts are considered are analyzed, determining what makes a material more critical.
- The consideration of circularity aspects: the circularity aspects refer to the considerations related to the presence of processes and practices related to circular economy (namely, recycling, remanufacturing, refurbishment, repairing, and reusage) for the assessed materials or components. It is evaluated whether these aspects are considered in the criticality assessment and, if so, in what terms they are.

In the Supplementary Materials, a table is presented where all the identified artifacts are classified according to each of the analysis dimensions listed above. The table was chosen as a means of representation to provide academicians and practitioners analyzing the raw material criticality assessment with a concise synthesis of the all the artifacts. In this way, they can evaluate them and select which artifact to deepen for their studies in a quick and comprehensive manner.

In the next paragraphs, the main findings for the analysis dimensions above are portrayed, exploiting mostly tabular representation and textual description when needed. Possible causes of heterogeneity among different artifacts are described in the discussion paragraph.

The conducted research was structured to be as comprehensive as possible, ensuring that any relevant result was not missed. The main issue in this sense remains the impossibility of including artifacts that are not uncovered and made public. In this case, it can be inferred that several companies worldwide will be using undisclosed and tailored criticality assessment tools and methods. The same may be possible for some countries. Nonetheless, it must also be considered that, unlike artifacts proposed in academic contexts, these are not peer-reviewed. Furthermore, even if they were accessible, unlike the included official reports, there is not a body of knowledge deeming whether these methodologies are relevant or not.

3. Results

The results of the systematic search provided 4052 documents. In the first step of the analysis, 3682 documents were discarded. In the second analysis step, 208 further works were discarded. In the end, 152 works were included. Finally, in the second complementary narrative review, 10 more relevant documents, all from official reports, were included. Thus, finally, 162 works were counted as relevant for the review. The selection process is shown in Figure 2.

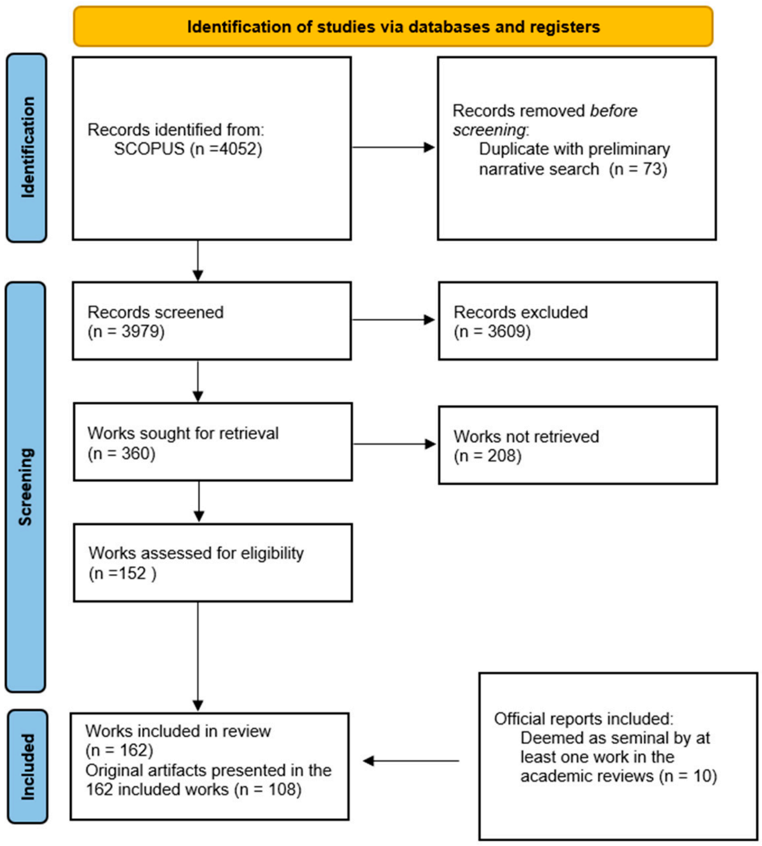

Figure 2. Process for the selection of works, portraying the steps of evaluation and selection of the works resulting from the literature review and the inclusion criteria considered at each step.

Not all the 162 works referred to the proposal of a novel criticality assessment tool or methodology. In some cases, an update, improvement or modification of a previously existing criticality assessment method or tool was proposed. From the 162 analyzed works, a total of 108 different assessment models and tools were identified. In the references presented in the annexed table, when more than one work refers to the same artifact, the reference presenting the latest version of the artifact is provided.

The risk of bias was assessed as low for all the analyzed artifacts, for the reasons already described in the methods paragraph.

3.1. Analysis of Criticality Scope, Criticality Dimensions and Shape of the Artifacts

Analyzed models, methods, and tools are reported and classified according to the described analysis dimensions in the Supplementary Materials section. For each of them, an in-depth analysis was carried out to classify them according to the mentioned analysis dimensions. The resulting table can serve as a mapping of the current state of the art of the criticality assessment, to orient academicians and practitioners in identifying the criticality assessment tool or methodology most fitting with their needs. Furthermore, it can serve as a tool to better identify eventual literature gaps to be filled.

Out of 108 analyzed tools and methodologies, 88 were published for the first time through academic documents.

In Figure 3, the trend in artifact proposal through the years is presented.

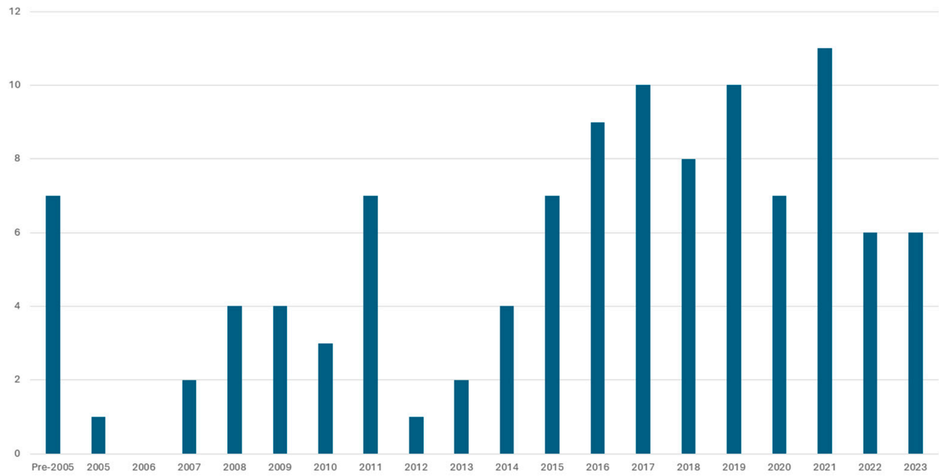

Figure 3. Trend in the frequency of the publication of criticality assessment artifact proposals through the years.

New models and tools to assess criticality started being developed in a considerable number since the late 2000s. The yearly number of developed artifacts started ramping up towards the latter half of the previous decade.

Concerning the considered scope, the results are portrayed in Table 1.

Table 1. Number of artifacts per each identified typology of criticality scope in the results of the conducted literature review.

Criticality Scope	Number of Artifacts with That Scope
Company level	7
Country level	53
Global level	29
Product level	6
Flexible scope	5
Undefined	1
Specific for an industrial sector	32, of which 24 focused on energy sector. The other considered industries were automotive (five artifacts), the production of spintronic memories (one case), and recycling of LED components (one case). In one case the artifact was specific for both the e-mobility and Renewable Energy Sources sectors.

As to what concerns the CDs considered, there is a big heterogeneity in terms of the nomenclature used. The CDs considered the most are detailed as follows:

- Unavailability risk, found as a CD in 102 artifacts. This refers to measuring the risk that the considered material would not be available in the right quantity or at the right time. Under the umbrella term of unavailability risk that has been placed on different CDs, it includes, among the others, supply risk, substitutability, price fluctuation, and ratio between forecasted demand and forecasted available resources. In those cases where the artifact considered two or more of these dimensions as two or more separate CDs, they have been merged here under the label of unavailability risk.
- Economic impacts, counted 42 times. This is a CD referring to the economic consequences of the absence of the assessed materials and thus to the economic dependence on them. Its nature may change from one work to the other, mainly according to the considered criticality scope.
- Environmental impacts: Under this label, the impacts on the environment that have occurred due to the extraction, working, transportation, usage, and disposal of the assessed material are considered. Environmental impacts were counted 20 times in the analyzed artifacts as a main CD.
- Social impacts were counted seven times. Here, the evaluation of the impacts on people's health and wellbeing related to the extraction, working, transportation, usage, and disposal of the assessed material were included.

Further CDs that appeared only in one or two artifacts are summarized in Table 2.

Table 2. Detailed description of criticality dimensions (i.e., factors deemed as directly impacting the criticality of the material) found in only one or two of the artifacts resulting from the conducted literature review.

Criticality Dimension	Number of Artifacts in Which It Was Found	Description	Sub-Dimensions or Parameters Composing It
Demand growth	1	Forecasted increase in demand for that specific material.	None
Thermodynamic rarity	1	Amount of exergy needed to obtain a given material from a completely degraded state [15].	None
Market stability	1	Robustness of the mineral to sudden market changes by quantifying its price volatility [16].	Mineral's price
Recycling barriers	1	Main barriers encountered when recycling metals, displayed in a qualitative manner.	None
Recyclability Index	2	Recycling potential of the considered material in the considered product.	In [17], (i) the statistical entropy of the material in the product, (ii) material grading, and (iii) the total number of materials are considered.In [18], it is qualitative.
Technology Index	1	Availability of technologies to be used to recover CRMs from LED lamps and their related environmental impacts.	They are (i) technology availability, (ii) environmental impacts, (iii) mechanical processing costs, and (iv) metallurgical processing costs.
Strategic relevance for the country	2	Necessity of the material in sectors strategic for the considered country.	None
internal availability	1	Quantity of materials available for mining in the considered country.	None
Risk for strategic employment	1	Relevance of that material for national industries in terms of the employment it provides.	None
Relevance for future technologies	1	Relevance of that material for technologies forecasted to be strategic for the future of the industries in the considered country.	None

Table 2. *Cont.*

Criticality Dimension	Number of Artifacts in Which It Was Found	Description	Sub-Dimensions or Parameters Composing It
Reputation risks	1	Eventual negative influence on corporate reputation coming from usage of that material.	The parameters are (i) the environmental impact of raw materials; (ii) Human Development Index; (iii) regulations with respect to conflict materials
Material risk indicator	1	Risks related to material itself and not to how it is supplied.	The parameters are (i) the lack of substitutability, (ii) global consumption levels, (iii) global warming potential, and (iv) total material requirement.
Resource Index	1	CD related to the economic convenience of recycling certain CRMs.	The considered parameters are (i) economic impacts, (ii) supply risk, (iii) metal value.
Material risk	1	Risks related to material itself and not to how it is supplied.	The considered parameters are (i) substitutability, (ii) strategic relevance for the country, (iii) environmental impacts, (iv) global consumption levels, (v) global warming potential from extraction and production, (vi) total material requirement for extraction and production, and (vii) price.
Thermal resistance	1	Technical parameter related to the functionality of the alloy	None

Concerning the form of the output provided by the artifacts, the results that emerged are listed in Table 3. In five cases, the artifact presented two different forms for the final output.

Table 3. List of the identified typologies of criticality assessment artifact outputs, with their description and the number of artifacts identified through the literature review in which they have been found.

Artifact Output	Description	Number of Artifacts in Which It Was Found
Synthetic indicator	A single synthetic indicator that attempts to quantify criticality.	38
Multi-metrics indicators	A bunch of different indicators not merged in a synthetic criticality proxy.	25
Two-axes matrix	Parameters are summarized in two CDs and the final output is a plotting of the materials in a two-axes matrix.	23
Disaggregated	The CDs to be analyzed and assessed to define material criticality are just presented, and no further indications about the construction of precise indicators were provided.	14
Three-axis matrix	Parameters determining criticality are summarized in three CDs and the final output is a 3-axes matrix where materials are plotted.	5
Framework	An entire elaborated framework.	2
Demand–supply chart	A demand–supply chart where present and forecasted demand and supply of CRMs are drawn.	1
Clustering diagram	A Venn diagram to cluster the materials into different groups.	1
Sankey diagram	A Sankey diagram quantifying material flows.	1
Network analysis	A network diagram of the considered industry chain, to identify the most central and thus critical actors along it.	1
Yes/No indicators	A series of binary answers (yes or no) to a series of questions.	1
Qualitative	Materials are clustered according in a qualitative way according to the authors' opinion.	1

Concerning the criteria used to assess if a material was either critical or not, the main found mechanisms are described in Table 4.

Table 4. List of the identified criteria and mechanisms to assess criticality found in the artifacts uncovered through the conducted literature review, with a description and the number of artifacts in which each of them was found.

Criterion	Description	Number of Artifacts in Which It Was Found
Threshold	A threshold for the values that the quantified indicator or indicators is set. If a material obtains values for those indicators above or below these thresholds, it is deemed as critical.	6
Benchmarking	A benchmark between the different scores obtained by the assessed materials is carried out. In this case, materials are not classified as either critical or non-critical, but criticality is evaluated in a relative comparison among the marks obtained by the materials.	55
Left to interpretation	A precise mechanism or criterion to assess if a material is either critical or not is not present.	20
Clustering	In some cases, materials are plotted on a chart or on a graph, and clustered. If they belong to a certain cluster or clusters, they are deemed as critical. In other cases, the materials are inserted in a table or in a scheme, and clustered in groups, according to their criticality.	27

3.2. Environmental Sustainability Aspects in Criticality Assessment

Concerning environmental impacts in the evaluation of criticality, it was found that 75 artifacts out of 108 did not consider it. For the remaining 33 artifacts, different ways of considering environmental impacts and of defining their relationship with criticality emerged, as described in Table 5.

Table 5. List of the different roles that environmental impacts have been found to have in assessing criticality in the criticality assessment artifacts found in the literature review, including the number of times each typology of role was spotted and the description of its role within the criticality assessment.

Role of Environmental Impact	Number of Occurrences	Description of the Role
As a main criticality dimensions	19	In these cases, environmental impacts were considered as one of the main dimensions making a material critical
As a parameter of social acceptance	4	Here, environmental impacts were considered only for the impacts they may have on public opinion. Here, social acceptance and the related risks were considered as a main CD or sub-dimension. In one artifact, environmental impacts were both a component of social acceptability and a main CD
As a parameter of unavailability risk	5	In these artifacts, environmental impacts were considered as a parameter of the unavailability risk CD. Here, environmental impacts were moreover considered under the label environmental country risk, i.e., the risk that mining activities are banned from a certain countries due to their environmental impacts.
As a sub-dimension of sustainability impact	1	In a single case, environmental impacts were considered as a sub-dimension of an index, called sustainability impact, in which both social and environmental indicators are embedded [19]
As a parameter of technology index	1	In one artifact, environmental impacts were one of the four parameters defining the technology index CD [17].
As a parameter of material risk	1	In this case, environmental impacts are considered as a parameter of a CD named material risk [20].
As a parameter of material risk	1	In [21], environmental impacts are a parameter of the CD material risk together with consumption level, substitutability, and total material requirement.
As a parameter of economic impacts	1	In one artifact, environmental impacts were considered as a parameter of the economic impacts CD.
Indirectly considered	1	In one case, the artifact proposed to assess materials criticality was conceived to be used complementarily with LCA methodology [21]. Therefore, it can be stated that in this case the artifact considers environmental impacts indirectly.

In many works, the exploitation of Ecoinvent databases for the assessment of the environmental impacts caused by the utilization of a certain material is proposed. In [7], the use of the ReCiPe method is proposed, considering a cradle-to-gate approach. ReCiPe utilization is also suggested in [22–28]. Then, the impact values computed by means of the ReCiPe method are merged in synthetic indicators and then considered as a CD. In all these artifacts, the environmental impacts index is composed of two sub-dimensions, i.e., human health and impacts on ecosystem. In [22], ReCiPe is suggested to be used as a second-choice method. The first-choice method is sourcing data from the World Wildlife Fund. In other cases, an integration between the LCA methodology and criticality assessment is attempted [21,29–31]. In [29], criticality is conceived as provided only by unavailability risk and economic impacts. These works are partly based on precedent, the purely theoretical discussions about integration between LCA and criticality assessment performed in works like [32,33]. Nonetheless, it is attempted to incorporate it inside the framework of the life-cycle sustainability assessment (LCSA). The aim is stated to be providing a product-specific evaluation of product–system vulnerability. In this case, the criticality is treated as a purely economic indicator, but the interesting consequence of this approach is that all the three sustainability aspects of the Triple Bottom Line (environmental, social, and economic) would be considered in the LCSA framework for CRMs.

In [30], the focus is placed on integrating the indexes that measure unavailability risk in the short term (10–30 years) in LCA, as the scarcity approaches typical of LCA are focused only on the long term. In this work, the use of an eco-cost model is proposed. In this way, it would be possible to merge socio-economic end-points with environmental end-points in a single synthetic indicator. A final criticality score would be obtained, accounting for unavailability risk, environmental impacts, and social impacts, all of them considered as components of criticality.

In [21], some methodologies to assess criticality are proposed. They focus on the aspects of unavailability risk, vulnerability, and economic impacts. They are conceived and considered to be used as complementary to LCA, in particular to the global warming potential impact category. In this case, the idea is that criticality and environmental impacts are two separate concepts, but that they should be considered concurrently, each with the same relevance. The GeoPolRisk methodology is another attempt at building an LCA midpoint and end-point referring to criticality [34,35]. The end-point is focused on supply risk and price elasticity.

In [31], the objective declared involves exploiting LCA to assess the environmental impacts of CRMs, considering them as a CD together with the economic and unavailability risk aspects. Unavailability risk and economic impacts are integrated into LCA by means of ad hoc characterization factors. It is also stated that the inventories used for LCA contain the information needed to assess the utilization of CRMs throughout their life cycle, to then characterize their relevance in terms of economic impacts. The basic idea is to attempt, at an impact assessment level, to determine the application of indicators used for the assessment of criticality and to develop LCA characterization factors, which would reflect the socio-economic and geopolitical perspectives. The final result is structured, and four different characterization factors are considered for resource assessment, each of them representing a different perspective: (i) resource depletion, (ii) socio-economic and geopolitical concern, (iii) socio-economic concern and depletion, and (iv) environmental concern. In doing so, Ref. [31] tries to tackle the elements related to relativity, subjectivity, and the temporary nature of the criticality assessment. To do so, characterization factors are crafted based on indicators referring to a global level-assessment and based on experts judgment; no elements deemed as subjective, like thresholds, are used, and frequent updates of the characterization factors are suggested.

Another indicator is national environmental risk. In this case, environmental impacts are considered only as a parameter of unavailability risk. The national environmental risk is a measurement of the risk that material supply may be restricted due to environmental protection regulations in the producing and mining countries. From a conceptual point of view, in this case, the environmental impacts are not directly related to criticality, but indirectly impact it through the unavailability risk. In [36], the environmental country risk is computed through the Herfindahl–Hirschman index (HHI) of concentration and the Environmental Performance Index developed by Yale University, which provides the average sustainability performance of a country. Ref. [37] uses national environmental risk as a CD.

Environmental performance index, besides [36], is used in few artifacts. In [8], it is used as a parameter of social acceptance. In this artifact, apart from environmental performance index as a main CD, environmental impacts are also considered. In [38,39], it is used as a parameter of unavailability risk. In [40], the environmental performance index is normalized and used with the HHI to compute the environmental risk, which is one of the considered CDs. In [41], the environmental performance index is used as a weighting coefficient of GDP while computing the investment potential sub-dimension;

Further interpretations of the role of environmental sustainability are presented below, as they have been found in other artifacts.

In [42], the proposed artifact is exclusively focused on the environmental impacts aspects related to the criticality of raw materials. The methodology, aiming to be comprehensive, identifies eleven indicators. This methodology is found to be implemented by [43] as well, complementary to the artifact proposed there.

Ref. [44] is focused on the photovoltaics sector. Here, the environmental impacts are considered as one of the main CDs, and its three indicators are tailored specifically for the photovoltaics industry.

In [19], the environmental impacts are considered only for what concerns the contamination factor, computed through the anthropogenic flows proposed by [45], as a ratio between anthropogenic flows and natural flows related to the assessed material.

In [46,47], a qualitative approach of assessing environmental impacts is proposed. In the former, five indicators related to five environmental impact categories are considered. The assessment of each of these parameters was provided by experts in scale form, considering low impact, medium impact, and high impact. In the latter, materials are assessed in a qualitative way against the SDGs, and their criticality evaluated basing on the results. A qualitative but more structured approach has been used for evaluating the environmental impacts of materials in [18], considering element toxicity.

In [27], in addition to the already mentioned ReCiPe methodology, one more parameter related to environmental impacts is computed: local environmental justice. This indicator starts from the worldwide governance indicator datasets, considered as a proxy of for potential occurrence of environmental issues.

In [48], the focus is on materials for low-carbon technologies. In this case, the environmental impacts are quantified by means of how much CO_2 emissions reduction can be expected by the technology for which the assessed material is needed.

Finally, the last analysis dimension was focused on the consideration of the presence of circularity practices. In the analyzed artifacts, it was found that, out of 108 models, methodologies, and tools, in 53 cases the presence of circularity practices was not considered. For the remaining cases, the following results were found:

- As a parameter or sub-dimension of unavailability risk: in 50 artifacts, the presence and quantification (mostly in terms of the quantity of the involved materials) of circularity practices was considered directly or indirectly as a parameter or sub-dimension influencing the unavailability CD. Indeed, the availability of further sources of materials or components, like those coming from recycling, repairing, or remanufacturing, will automatically decrease the risk that those materials will not be available when needed.
- As a CD: in five cases, circularity practices were given a more relevant role in the assessment, by covering the role of a CD, considering not only the consequences in terms of unavailability risk reduction, but also in terms of environmental impact reduction.

- As a parameter of social sustainability: in one case [47], circularity practices are viewed as positively impacting on the social sustainability associated with CRMs' life cycle (as they are typically a more socially sustainable alternative to mining activities).
- As a parameter of environmental impacts: in one case, it was considered as a parameter of the environmental impact CD, by quantifying the energy saved through recycling practices [44].

4. Discussion

It is interesting to note that the vast majority of the analyzed works were focused on global and country levels. On the one hand, this suggests that the relevance of criticality assessment is particularly felt for political and geopolitical reasons. Nonetheless, these topics need to be assessed also at a company level. Indeed, enterprises need to deal directly with the issues related to material criticality [2,49]. Another possible explanation for the low number of the company-level artifacts found is that several enterprises may be performing criticality assessments internally, not disclosing the adopted methodologies.

Among the 33 artifacts found to be sector-specific, the vast majority of them were focused on the energetic sectors. While this sector is undoubtedly extremely relevant and very sensitive to material criticality issues [25,50–52], it is widely known that CRMs are massively impacting other strategic industries as well [5,52]. The specificity of the sector is crucial, since how the concept of criticality is defined is dependent on this aspect, and, thus, what CDs are included and how they are defined.

Concerning the considered CDs, in addition to unavailability risk, economic impacts, and environmental impacts being adopted in many different artifacts, most CDs appeared only few times, and most of them only once or twice. The choice of CDs to be considered by the different artifacts identified as being mainly dependent on four factors:

- The considered criticality scope: different scopes embed different perspectives on criticality and thus different CDs to be considered.
- The consideration of a specific industry: the concept of criticality is defined in different ways in different sectors, which translates to the consideration of different CDs.
- The objective of the artifact: If the objective of the artifact is simple in its application and presents results that are immediately understood, then it would be reasonable to use conceptually simple CDs, composed in a mathematically simple manner. In other cases, CDs may be conceptually more complex (e.g., [15]) and their computation mathematically less simple.
- Authors' opinions and ideas: since a univocal universally accepted concept of criticality is missing, different authors decide to include or exclude certain CDs in their assessment artifacts.

Furthermore, even if two different artifacts are considering the same CD, they may be doing so by using different indexes and by quantifying the CD with different parameters and methods.

Another interesting consideration concerns the adopted criticality criteria. In most cases, the definition of a material as critical or non-critical was either left to interpretation or relative. Considering criticality as a relative concept, means that criticality is assessed through benchmarking: the materials are ranked from the most to the least critical, and are more or less critical only in relations to other materials criticality. The underlying logic involves a definition of what is critical and what is not based on relativity: a material will be deemed as critical only if it emerges as more critical than most of other materials. On the contrary, in the cases where the criterion was based on a threshold or on clustering, the underlying logic is of a conceptually absolute criticality: a material is critical if it respects certain conditions, independently from how critical other materials are. The two approaches are thus related to two different ontological conceptions of criticality. This difference has important consequences on how the criticality of materials is assessed, and thus, on the concrete decisions taken at policy and industrial levels. It is crucial that a univocal ontological conceptualization of criticality is reached for the scientific discussion to be sound and consistent.

Regarding the presence of environmental impacts as a factor influencing material criticality, it was noted that it was considered by several artifacts. Nonetheless, heterogeneity of the typology of the connection between environmental impacts and criticality was found. This is due in part to the different contexts of the different artifacts, and in part to a lack of definition of the relations between these two concepts.

From the analysis described in paragraph three, it clearly emerges that environmental impacts are considered in several different ways within a material criticality assessment, often including impacts not only on the environment but on human health as well (e.g., [30]). When environmental impacts are considered only through national environmental risk, the real focus is on unavailability risk, and environmental impacts are not considered as a component of the criticality concept [36]. A similar pattern can be recognized when environmental impacts are considered through the environmental performance index [40,41,53]. Indeed, this index is very generic and unprecise. In other cases, as described in paragraph three, environmental impacts are given a direct connection with the criticality concept, but this is assessed in qualitative or unstructured ways. The artifacts that provided the most complete and objective way of assessing environmental impacts were those exploiting LCA computation techniques like ReCiPe, and considering several impact categories [29–31,54]. Nonetheless, it is important to be aware of the fact that LCA can be misleading when computing depletion scores as, typically, allocation procedures during data inventory might lead to result contamination between different metals [30]. The main reason behind the choice of using ReCiPe methodology or the national environmental risk lies in the relevance that the artifact is providing to environmental impacts. Indeed, in all of the cases where ReCiPe was suggested, environmental impacts were seen as directly related to criticality. Therefore, the impacts are directly assessed and considered as directly contributing to criticality. In all artifacts implementing national environmental risk and environmental performance index, environmental impacts are seen as an aspect potentially influencing unavailability risk, through the application of environmentally friendly legislation. These two presented perspectives appear to be the main interpretations of the role of environmental sustainability in relations to criticality.

Some further reflections concerning the nature of the relations between environmental impacts and criticality can be inferred from works where the integration of a criticality assessment in the LCA methodology was attempted [29–31,54]. In all of them, the analysis is only methodological, as it is proposed how LCA and criticality assessment could be merged in a broader and more comprehensive methodology. The epistemological and ontological considerations around the relationship between criticality and environmental sustainability are not explicitly taken into account. Nonetheless, a possible inference can be made, as, in most of these methodologies, criticality is treated as a novel end-point of LCA or LCSA. This approach would suggest considering criticality as a component determining material sustainability, conceiving sustainability itself as it is conceived under the Triple Bottom Line (TBL) paradigm (i.e., composed of economic, social, and environmental aspects).

The three main identified perspectives of relations between environmental sustainability and criticality, respectively, embedding ReCiPe methodology in the criticality assessment without referring to LCA, using the national environmental risk and performance index, and merging criticality assessment into LCA, are summarized in Figure 4.

Concerning the last analysis dimension, related to the consideration of circularity practices, it was found that in the vast majority of the cases where circularity was considered, it covered the role of a parameter of unavailability risk. Paradoxically, only in one case were the impacts on environmental sustainability considered.

One more consideration is related to how a serious attempt to assess criticality for entire components cannot be found in the literature. Only one case was found [53], where the analysis objective was not the criticality of the materials but the criticality of the components. Nonetheless, a mere weighted sum of material criticality was the way in which the component criticality was computed.

Finally, the lack of sound epistemological or ontological motivations that the vast majority of works present when introducing CDs, sub-dimensions, or parameters of criticality can be addressed. They are typically just integrated in the models or tools, without any explanation or motivation about their inclusion. This can be inferred to be the consequence of a lack of solid theoretical background for the topic of criticality, which is also the cause of the numerous inconsistencies existing among different criticality assessment methodologies.

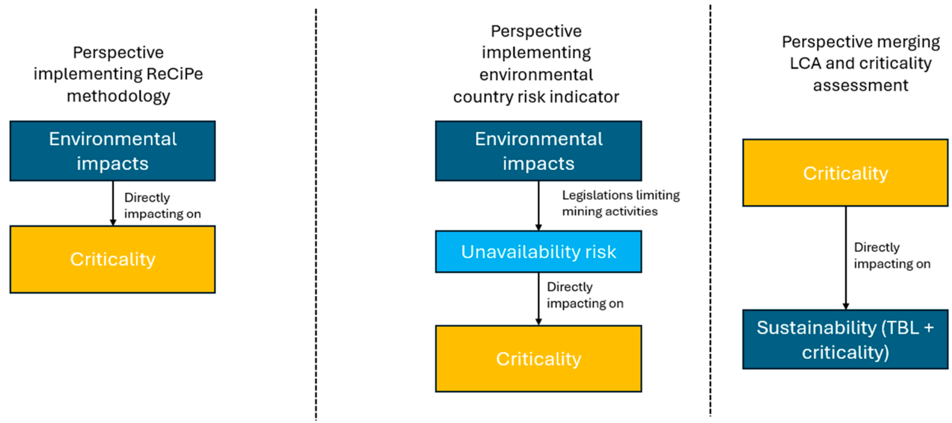

Figure 4. Scheme of the three main perspectives of the relations between environmental sustainability and criticality that were identified through the conducted literature review of criticality assessment artifacts. For each of the three modalities, the blue box represents the concept of environmental sustainability, the light blue box represents the concept of unavailability risk, and the yellow box represents the concept of criticality.

5. Conclusions and Future Research

In this work, the heterogenous literature related to material criticality assessment methods and tools has been reviewed.

In this work, emphasis has been placed on the consideration of environmental sustainability. A variety of approaches to include sustainability in the criticality assessment has been identified and discussed. The most promising possibility, in terms of completeness and the precision of environmental impacts inclusion, seems to be the merging of criticality assessment methodologies with LCA. In this case, considering criticality as a result of unavailability risk and economic impacts and integrating it in LCA or LCSA as an end-point or as an impact category seems to be where the literature is converging. Even though there are not explicit epistemological or ontological considerations about this, it is possible to infer that the underlying logic considers criticality as a factor of sustainability, to be considered together with environmental and social sustainability when evaluating certain materials or products.

The conducted classification of the presented artifacts is an attempt at providing a picture of the heterogenous literature. In this way, academicians, practitioners, policy makers, and other interested parties can better orient themselves within this topic, in the processes of criticality assessment artifact exploration, analysis, selection, and development. Furthermore, some potential gaps to be filled by future works have emerged, like the lack of artifacts focused on a company- or product-level scope, or of artifacts tailored for sectors massively impacted by CRMs, like mass electronics. Another interesting suggestion may be a thorough discussion around the ontological difference between the relative and absolute conception of criticality, and the practical consequences of assuming one vision or the other.

This work is not exempt from limitations. As mentioned, very few contributions from the academic community to perform a company-level criticality assessment have been found. Nonetheless, it is reasonable to assume that several enterprises perform criticality assessments of the raw materials they embed in their own processes, but the utilized methodologies are not disclosed and thus cannot be found by means of a literature review. Furthermore, while this work focuses on the relationship between concepts of criticality and environmental sustainability, different works may focus in a similar way on the relationship between criticality and social sustainability and acceptance in the future. In addition, unlike other reviews (e.g., [1]), this analysis is not focused on aspects like the data requirements of analyzed methodologies and the time horizons they consider.

Finally, the future direction of the criticality assessment can be reflected upon. From the significant heterogeneity among different artifacts that has been highlighted throughout the work, it can be inferred that the different contexts and needs for which criticality assessment tools and methodologies are created require them to have different features, forms, and CDs. Thus, it is crucial that the scientific community makes sure to take a direction that allows different needs and priorities related to criticality assessment emerging from different industries and contexts to be satisfied. To do so, criticality assessment models and tools should be tailored for specific contexts, industries, and even companies. Nonetheless, the obvious risk of taking this direction is the proliferation of even more extremely heterogeneous assessment tools and methods, presenting deep inconsistencies among them. Thus, it is necessary to make the literature less diverse, as this work attempts to partially do, and, if possible, create guidelines about how future tailored criticality assessment tools and methodologies should be developed. The only way of developing such guidelines is to first consolidate a scientifically solid theoretical background for the criticality topic, to provide appropriate theoretical lens to those willing to developing new assessment models and methods. This ought to be one of the major topics for the future of this knowledge domain. The suggested future development of this knowledge domain is schematized in Figure 5.

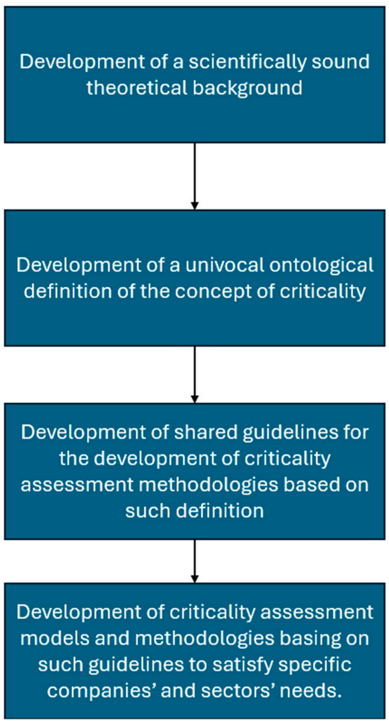

Figure 5. Suggested future development of the criticality assessment knowledge domain, in order to try to better structure the process of the development of criticality assessment artifacts on a foundation of shared guidelines.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/resources13090131/s1, Table S1 List and classification of all analyzed criticality assessment models, methodologies, and tools.

Author Contributions: Conceptualization, D.P. and P.R.; methodology, D.P. and P.R.; validation: S.T.; formal analysis: D.P., P.R. and S.T.; investigation: D.P., P.R. and S.T.; resources: P.R.; writing-original draft and preparation: D.P.; writing-review and editing: D.P.; visualization: D.P.; supervision: P.R. and S.T.; project administration: D.P.; funding acquisition: P.R.; All authors have read and agreed to the published version of the manuscript.

Funding: Funded by the European Union. The views and opinions expressed are, however, those of the author(s) only, and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency (HADEA). Neither the European Union nor the European Health and Digital Executive Agency (HADEA) can be held responsible for them. The Grant Number is 101091490 from the Horizon Europe Research and Innovation Programme.

Co-funded by the European Union

Data Availability Statement: The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Conflicts of Interest: The authors declare no conflict of interest.

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