

Sustainability Indicators and Indices in Mining: A Critical Approach

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Abstract— This study aims to deepen the discussion on sustainability mining using existing indices and indicators, and investigate the development of indices and indicators specifically for Brazil. This research is driven by the need to measure and understand sustainability in mining, and to derive solutions and alternatives for minimizing adverse impacts. An exhaustive literature review of international peer-reviewed academic articles published over the past 47 years was performed. An overview of the relevant literature was developed via a bibliometric approach, using VOSviewer. Incomplete areas, related to building a mining index structure that is able to measure and understand the sustainability of mining and enterprise management, were observed. We found that it is unnecessary to develop other sustainability indicators for mining, since the existing indicators are abundant, comprehensive and flexible for application in different regions and mineral substances. However, we still need to develop new sustainability indices that can assess this issue.

I. INTRODUCTION

Mineral assets are essential to human life (SHEN et al., 2015; PEDROSA BATISTA et al., 2019; GOKHBERG et al., 2020). Mining is the foundation in the production chain of popular industrialized products. Mineral production plays an important role in several segments of the Brazilian industrial sector. According to the National Mining Agency (ANM) (ANM, 2019), there was a 15.4% growth in mineral production in the first half of 2019, compared to 2018. This growth represented 20.8% of national exports of the mineral extractive industry during the discussed period. According to the Ministry of Mines and Energy (MME) (MME, 2020), Brazil extracts about 80 minerals used in various production chains in more than 2,300 municipalities. Mineral products are crucial for

various industries, including automotive vehicles, civil construction, furniture, and electronics. Yellishetty et al. (2008), Zhao et al. (2014), Delgado et al. (2019), Silva et al. (2019), Exp sito and Velasco (2020), Kozlowski and Mackiewicz-Talarczyk (2020), Ferreira et al. (2020), Shershneva et al. (2020), He et al. (2020) and Dias et al. (2020), state that production chains of various industries such as agriculture (fertilizers, soil correctives and remineralizers), food (input for food processing), electro-electronics, data generation and transmission, energy production and transmission, etc., require mineral substances.

Conversely, mineral substances have the potential to cause serious environmental, social and economic degradation (JONES et al. 2017; SRIVASTAVA et al.,

2020), posing challenges to sustainable development (AZAPAGIC, 2004). Local and occasional regional impacts include topographic modification, altered geological, geomorphological and hydrological conditions, vegetation and soil removal, and changes in fauna habitat. These impacts can lead to dust emissions, effluent discharge, noise, visual pollution, increased traffic volume, and significant amounts of waste material that affect water resources worldwide (WORRAL et al., 2009; DE MACÊDO COELHO et al., 2020).

Sustainability in mining emerges from the apparent paradox of reconciling the perspective of intergenerational guarantees (WCED, 1987) and the consumption of a finite resource. Worster (2016) questioned the prevailing vision of a world endowed with infinite natural resources and the ability to support an exponentially growing population. "We are no longer a small world on a big planet. Now we are a big world on a small planet, on which we have reached a saturation point" (ROCKSTRÖM, 2016, p. 4). Despite this new perception about the limits of regeneration of natural resources, the intuitive association between development and environmental degradation prevails. An antagonistic relationship between economic growth and environmental preservation, remains a challenge to be overcome (LAMBERTINI, 2016). Thus, the concept of "sustainable mining" requires adjustments that reflect the epistemological basis of sustainable development. The sustainability indices and indicators have significantly contributed in analyzing the activities that impact natural resources (CARVALHO et al., 2011). These indicators facilitate data gathering, data quantification, and decision making, which highlight their importance (VAN BELLEN, 2005; SILVA et al., 2010).

Azapagic (2004), Singh et al. (2007), Silva (2014), Shen et al. (2015), Aroudo Mota et al. (2017), and Dialga (2018), have developed sustainability indices and indicators for mineral substances. However, such indices and indicators (Viana, 2012; Long et al., 2016; Bui et al., 2017) found in the literature primarily focus on the business management of large enterprises and specific mineral substances. Thus, characteristics of mining activities, including clandestine activities, are often overlooked. Identifying the sustainability of the activity, regardless of the mineral substance, location, size of the enterprise, and operations licensing is crucial, since these factors significantly impact the socioeconomic and environmental spheres.

We aimed to conduct a literature review on indicators and sustainability indices for mining. Brazil is a region that specifically lacks studies on the development of such indices and indicators. Almost all existing research is conducted and aimed at international mining, and proposed

for specific contexts. Therefore, such activities have particular characteristics that differ from the Brazilian reality, attributed to parameters that lack available or obtainable data. This paper reviews and critically analyzes the literature to answer the following Research Questions:

QP1: Do existing sustainability indices and indicators accurately reflect the sustainability of mining in Brazil?

QP2: Is developing new sustainability indices and indicators for assessing mining in Brazil necessary?

II. MATERIALS AND METHOD

A temporal limit was established, addressing the literature published over the past 47 years (the first articles identified with the research approach), from 1973 to 2020. This literature review was guided mainly by academic search engines that encompass large research databases such as ScienceDirect (Elsevier), Scopus (Elsevier), SpringerLink (Springer), SciELO.ORG, and Google Scholar.

The nomenclatures were defined according to identical terms and searched in the context of sustainability in mining, for finding the largest number of relevant documents. Peer-reviewed articles were sought, written, and classified in Portuguese and English, according to the criteria presented in Fig. 1. It is noteworthy that the secondary references were consulted in order to identify if any research developed indexes and indicators with the objectives of this research. As these references addressed another focus, they were not accounted for in the bibliometry.

Several publications focused on approaches that are beyond the scope of this research. Several publications on sustainability in engineering and corporations, the ecological footprint of renewable resources, and Life Cycle Assessment (LCA) of materials, were discovered. A set of references was automatically discarded based on their title and abstract, as they addressed challenges that were irrelevant to mining (e.g. "data mining" and "text mining"). Articles deemed "relevant" are decided based on the subjective authors' criteria; hence, unintentional omission of important publications is possible. However, the authors have endeavored to consider most of the topics and case study examples related to sustainability, and the use and development of indices and indicators in mining.

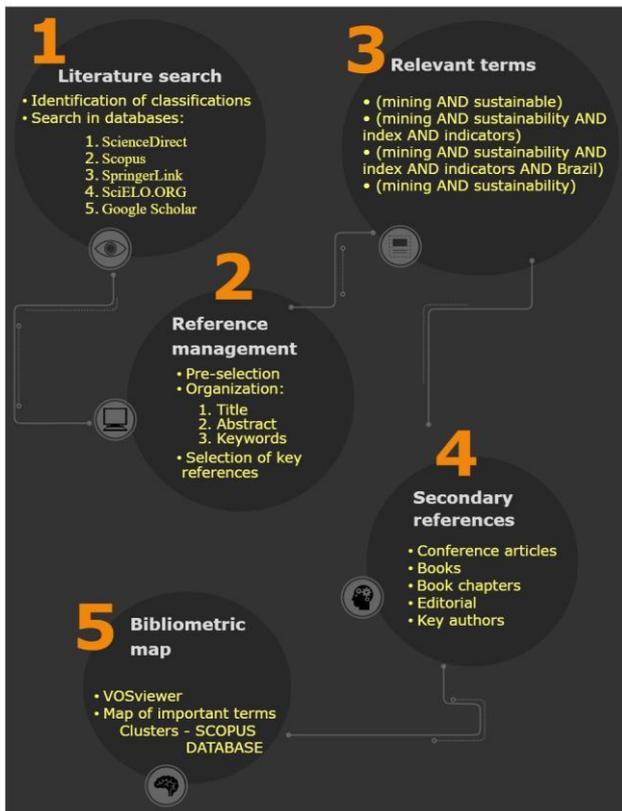


Fig. 1: Flowchart with the defined criteria.

The Scopus database was explored to conduct a detailed metric search on the proposition of sustainability indices and indicators for mining, in existing research. The Scopus database is considered comprehensive, relevant, contains the world's largest database of abstracts and citations of peer-reviewed literature, and uses bibliometric tools to track, analyze and visualize the research (DE OLIVEIRA and GRÁCIO, 2012; SCHOTTEN et al., 2017; SANTOS and XAVIER, 2018). Thus, the other databases, Science Direct, Springer, Scielo.ORG and Google Scholar were only consulted for purpose of finding research with the focus of this unidentified article in Scopus.

Finally, we used VOSviewer, a software application developed by Van Eck and Waltman (2010), for constructing and viewing bibliometric maps. It was applied to facilitate the visualization of the terms most cited by the documents researched in mining sustainability, and a map of keywords was built based on co-occurrence data provided by Scopus. VOSviewer only used this database because it facilitates the application of precise bibliometric techniques. The map generated provides color-based term density clusters, ranging from red, yellow, green to blue, respectively, indicating the highest citation frequency of these terms and their importance.

III. THEORETICALS STUDIES

3.1 Sustainability Indices and Indicators

In the 1970s and 1980s, indices and indicators were imported from the economic to the environmental sphere by governments and international organizations, to disseminate information on environmental conditions (FRANCA, 2001). In the 1990s, there was a considerable increase in the search for such indices and indicators, especially by governmental and non-governmental organizations, research institutes and universities. However, the theme was relatively new to the academic community. The concepts, experiments, and research results were recent, and most were developing. Consequently, the search for indices and indicators became unreliable due to the lack of quantitative assessment methodologies and the limited availability of environmental statistical data (MARZALL and ALMEIDA, 2000; MIKHAILOVA, 2004).

The use of environmental indicators increased in the 2000s. Thus, indicators were used to inform the progress of a certain goal, such as sustainable development. Moreover, the use of such resources facilitates easy perceptibility of a trend or phenomenon (HAMMOND et al., 1995; VAN BELLEN, 2005). Santos (2004) states that an indicator facilitates identification of reality through a set of data that represents parameters capable of demonstrating the environmental conditions. Thus, sustainability indicators structure information on key points and trends for sustainable development. Controlling the changes in the sustainability dimensions is possible using the information provided by such indicators (VAN BELLEN, 2004; RAMETSTEINER et al., 2011). Therefore, the indicators are fundamental for decision-making, especially when compared to other methods of obtaining information (GALLOPÍN, 1996).

A sustainability index is generated from a set of indicators, mathematically synthesizing a series of quantitative and/or qualitative data associated with sustainable development. Each index generates a numerical value resulting from the mathematical operations, combined with the input information. This value is then analyzed by comparing with a standard scale, facilitating sustainability evaluation (MARZALL and ALMEIDA 2000; SICHE et al., 2007; KRONEMBERGER et al., 2008; VIEIRA and STUDART, 2009). Some authors such as Veiga (2010), Da Cunha Kemerich et al. (2014), Froehlich (2014), Barros and Barden (2019) and Ottoni et al. (2020) classify these indices as sustainability indicators. However, Van Bellen (2004) assumes that indices represent a higher level of aggregation of indicators. Thus, few references use the

terms “indicator” and “index” appropriately (GOMES et al., 2000; SICHE et al., 2007).

However, the indices and indicators should not be considered as solutions for all sustainability challenges (FERNANDES, 2004). Sustainability indices and indicators are useful in evaluating performance in the three sustainability dimensions (SHIELDS et al., 2002; SALDANHA, 2007). It is essential to observe the weaknesses and strengths of each indicator and index because these characteristics assist in choosing the most appropriate assessment parameter. To establish appropriate criteria of applicability, the indices and indicators must be built from existing problems. This allows for understanding critical aspects and obtaining the true potential, based on established parameters (DA CUNHA KEMERICH et al., 2014; LEONETI et al., 2016).

3.2 Sustainability Indicators in Mining

National and several international initiatives regarding the development of sustainability indicators in mining currently exist. Agenda 21 and the Mineral Sector, Ethos Institute, Global Reporting Initiative (GRI), European Commission (EC), and Mining Association of Canada (MAC) are corporate examples. Azapagic (2004), Worrall et al. (2009), Viana (2012), Marnika et al. (2015), Yaylaci and Düzgün (2016), are a few relevant academic authors. However, the existing indicator proposals of these organizations and authors for the mining sector are predominantly restricted to the preparation of corporate sustainability reports.

3.2.1 Proposals and use of indicators in mining

Viana (2012) analyzed the indicators proposed by the corporate initiatives for the mining sector and his considerations are largely negative regarding mining sustainability. The indicators are limited because they address few topics relevant to sustainability and several regarding mining management. Thus, having as main focus the social communication actions - sustainability reports (VIANA, 2012). Some sets of indicators have been proposed by several researchers, for the same purpose as proposed by the corporate organizations. The 131 indicators developed by Azapagic (2004) are exclusively for evaluating large mining companies, since they have a large number of employees, high investments, and financial resources, and significantly impact the economy and socio-environmental factors. Azapagic (2004) listed the main issues to be addressed by indices and indicators in the mining sector classified into the following three categories: economic, environmental, and social problems (Table 1).

Table 1: Key sustainability issues for the mining and minerals sector.

Economic problems	Environmental problems	Social problems
Contribution to GDP and wealth creation	Loss of biodiversity	Bribery and corruption
Costs, sales and profits	Emissions to air	Job creation
Distribution of income and wealth	Energy use	Employee training and skills development
Investments (capital, employees, communities, pollution prevention, and mine closure)	Global warming and other environmental impacts	Equal opportunities and non-discrimination
Shareholder value	Nuisance	Health and safety
Added value	Toxicity of the product	Human rights and business ethics
	Resource use and availability	Labor/management relations
	Solid waste	Relationship with local communities
	Water use, effluents, and leachates (including acid mine drainage)	Stakeholder engagement
		Distribution of wealth

Source: Adapted from Azapagic (2004).

Chen et al. (2015) determined mining sustainability indicators based on the use of mineral substances in construction in Beijing, China. Marnika et al. (2015) proposed indicators based on activity parameters and mineral processing for environmental protection areas. In both these research, the sustainability dimensions were significantly imbalanced. Fekri Yazdi (2014) proposed a general framework to assess sustainability and focused specifically on steelmaking activities using few indicators.

Worrall et al. (2009) developed sustainability indicators to particularly address the specific needs of areas abandoned after mining. Si et al. (2010) assessed environmental sustainability capacity in the coal mining industry. Thus the indicators used did not consider the three main pillars of sustainability. Yaylaci and Düzgün (2016) specifically evaluated indicators for coal mining. Bui et al. (2017) developed a framework restricted to the Asia-Pacific mining sector.

Regardless of the large number of indicators proposed and used by researchers and the corporate businesses in the mineral sector, most indicators are specific for certain regions and mineral substances such as coal and steel and intended for large enterprises. In addition, they are used disproportionately, by prioritizing one dimension of sustainability, inserting more indicators because of the reduction in other dimensions. Conversely, some studies proposed indicators out of sight. This increases the complexity of understanding the phenomena and consequently, corrupts the purpose of using indicators.

3.3 Sustainability Indices in Mining

A major challenge faced by the mining industry is ensuring minimal environmental impact, and the industry needs to adapt to sustainability to continue operation. To achieve sustainability, some indices have been developed to measure and evaluate sustainable performance and demonstrate continuous long-term improvement. Issues concerning business management, environmental performance, steel and steel industry, politics, economy and territory are specifically addressed in the development of mining indices (Fig. 2).

Long et al. (2016), Bui et al. (2017), Dialga (2018), Chen et al. (2020) and Angelakoglou and Gaidajis (2020) have recently proposed some indices for sustainability in mining. However, the number of proposed indices is observed to be lower than that of indicators, from the database searches. Therefore, the issues presented in Figure 2 were recent targets of extensive research for developing sustainability indices for mining. However, each index specifically addresses an aspect of mining.



Fig. 2: Schematic representation of the main topics addressed for proposing sustainability indices for mining. Adapted from the volume of the themes of studies published in the researched databases.

Thus, this section will be further divided into subsections to analyze and briefly describe the relationship of these issues with sustainability, using recent research.

3.3.1 Proposed mining indices

In this subsection, the main propositions of indices for mineral activity identified in the literature are addressed.

3.3.1.1 Economy, politics and territory

Bui et al. (2017) proposed the Indicator-Based Sustainability Assessment Framework (iSAF) to assess sustainability of the mining sector of Asia-Pacific Economic Cooperation (APEC) economies. The results suggested that iSAF is a suitable framework to prevent uncertainty and imprecision in economic decision making specifically for APEC, in relation to establishing the investments that would achieve sustainability. Dialga (2018) discusses the issue of sustainable development in countries with abundant natural resources, aiming to construct a Sustainability Index of Mining Countries (SIMC). The analysis indicated a lack of relationship between the values collected by states and their level of sustainable development. In addition, the number of indicators proposed (social - 5 and transversal - 2) for each dimension could be more balanced, to appropriately explain a phenomenon. In another study, Dialga (2019) establishes that the net impact of mining activity is difficult to measure. The tool most commonly used by companies subject to the requirement of Corporate Social Responsibility, is of the business group Global Reporting Initiative (GRI). This standard tool does not account for the specifics of the mining sector or the uniqueness of contexts. That is, addresses only managerial issues of enterprises and not issues that can make the performance

of sustainable activity, as indicated by Azapagic (2004). Hence, Dialga (2019) proposed the composite Mining Industry Sustainability Index (MISI) for policy making, to demonstrate the contribution of mining to the expansion of other economic sectors, the well-being of local communities, and management of environmental impacts. As a result, sensitivity and robustness analysis and correlation tests with other known indicators demonstrated the efficiency of the constructed index.

3.3.1.2 Steel and steelmaking

Long et al. (2016) highlights that there was no sustainable evaluation system designed specifically to meet the characteristics of the Chinese steel sector. The authors proposed the Sustainable Assessment (SA) system for helping Chinese steel companies in assessing their sustainability performance. The SA is based on the "triple-bottom-line" (the three pillars of sustainability - environmental, social and economic), however, the indicators used are specific to the steel industry. Singh et al. (2007) highlighted the difficulty in evaluating the performance of mining companies in the steel and iron segment based on a large number of sustainability indicators. The authors then developed composite indicators (which can integrate a large amount of information in simple formats) to assess the sector's sustainable performance from the proposition of the Composite Performance Index (CPI) for sustainability. According to Singh et al. (2007), the CPI allows the industry to identify opportunities for improvement and can be used in "benchmarking"; this is the process of searching for the best practices in a given industry, leading to superior performance.

3.3.1.3 Mineral business management

Viana (2012) conducted a nationwide study in which he measured mining sustainability by a management assessment system from the proposition of the Index of Mining Sustainability (ISM). The study concluded that a smaller quantity of indicators might be more appropriate to avoid repetition and irrelevance. Wang and Zhang (2018) conducted a study focused on coal enterprises in China, which aims for future healthy development, and establishing coal industries in a safe, efficient, and sustainable way is crucial. An index system based on Data Envelopment Analysis (DEA) was then developed to audit the progress of innovation and development of enterprises. The study resulted in twenty certified green coal mines, demonstrating success in the application and evaluation, to gauge the technological innovation of coal mines and improve safety, efficiency and sustainability. Despite the

good index structure, it does not directly reflect the dimensions of sustainability.

3.3.1.4 Environmental performance

Silva (2014) hypothesized that open-pit mining has an environmental performance similar to other economic activities that are not considered detrimental to the environment. Therefore, the proposal of the Environmental Performance Index (EPI) for open pit mining aims to compare the environmental performance of other economic activities with that of mining. Silva (2014) established that even if the environmental performance of the mining company has been below the performance of soybean culture, it was not incomparable to the performance of agricultural activity. This contradicts the popular opinion that mining causes higher environmental impacts than other economic activities. However, the index is intended for comparing economic activities with environmental issues, and not addressing the dimensions of sustainability.

Chen et al. (2020) evaluated and improved the situation of green mine construction in China while suggesting a future framework. This is based on the Direction-Pressure-State-Impact-Response (DPSIR) model, which is regarded as the dimensions of the framework and establishes an evaluation index system. The index evaluated the construction of green mines and the results indicated that their performance has improved significantly over the years. However, there were still some unresolved problems, such as the recovery rate of ore processing and the reuse rate of coal washing water. Angelakoglou and Gaidajis (2020) designed a study for strengthening the ability of mining industries to evaluate and improve their environmental sustainability performance, by introducing an index framework. The application of the framework resulted in the construction of the Mining Industries Environmental Sustainability Assessment Index (I_{ESAMI}), which proved satisfactory, according to the authors. However, the proposed index only considers the environmental aspect of sustainability. All indices addressed aim to achieve sustainability in mining (Table 2); however, some indices emphasize the environmental issue, while others focus on the economy of the region of the enterprises, innovation or quality of business management. Thus, these indices have advantages and disadvantages in their application to assess sustainability in what they are proposed.

Table 2: Summary of the information of the most relevant sustainability indices for mining, proposed by authors identified in the research.

Index	Approach	Indicators	Advantages	Disadvantages	References
CPI	Steel and steel industry	75	Enables opportunities for improvement to be identified	Evaluates only steel industries and uses a large number of indicators	Singh et al. (2007)
ISM	Mineral business management	70	Assesses the level of sustainability of mining enterprises	Uses high number of indicators and complex evaluation	Viana (2012)
EPI	Environmental performance	2	Compares the environmental performance of other economic activities with minerals	Uses a very small number of indicators and poor assessment of sustainability	Silva (2014)
SA	Steel and steel industry	17	Helping Chinese steelmakers to identify sustainability performance	Assessment of the steel sector only	Long et al. (2016)
iSAF	Economic and territorial	20	Prevents uncertainty and imprecision in decision making	Analysis focused only on economics	Bui et al. (2017)
DEA	Mineral business management	19	Evaluates the capacity for mineral technological innovation	Assessment only of the economic context of coal undertakings	Wang and Zhang (2018)
SIMC	Economic, political and territorial	19	Uses more comprehensive indicators in the dimensions	Assesses sustainable development in countries with abundant natural resources	Dialga (2018)
MISI	Economic and political	18	Demonstrates the local contribution of mining to economic and socio-environmental aspects	Aims only at political and economic issues	Dialga (2019)
DPSIR	Environmental performance	20	Evaluates the construction of green mines and the sustainability of the mineral industry	Structure with a greater environmental focus in the construction of projects	Chen et al. (2020)
I _{ESAMI}	Environmental performance	108	Improve the environmental sustainability performance of mining companies	Assesses only the environmental aspect of the sustainability of the mineral industry	Angelakoglou and Gaidajis (2020)

Source: Prepared by the author.

Generally, the studies considering sustainability indices proposed for mining follow the same trend as the proposition of the indicators; they are developed for large-scale activities, specific regions, themes, or widely used mineral substances such as gold, copper, coal, and steel.

Normally, these indices consider the most abundant minerals in their local region or their local economic value. For example, coal is one of the most commonly used primary energy sources, and its extraction and impacts are often targeted in sustainability criteria.

IV. DISCUSSIONS AND ANSWERS

4.1 Sustainability indicators and indices for Brazilian mining

National initiatives on sustainability indices and indicators for mining are at nascent stage. Viana (2012) and Agenda 21 and the Mineral Sector (MMA, 2004) were identified as Brazilian studies that have developed indicators. The authors of the present research hold a similar stance to that of Viana (2012): despite the existence of numerous indicators, several of these are not adapted to Brazil; thus, some issues remain overlooked.

The visual and noise impact caused by mining operations, the percentage of area occupied by facilities within Areas of Permanent Preservation (APPs), and the Financial Compensation for Exploitation of Mineral Resources (CFEM) are such issues. Others indicators are considered complex since their access is restricted to large corporate groups of mining companies as post-exhaustion economic alternatives and social decommissioning of the mine (VIANA, 2012). Of the indices researched and addressed, only the Environmental Performance Index for open pit mining (IDA), proposed by Silva (2014) and the ISM by Viana (2012), were developed and applied nationally. However, rare research for the use of indicators and indices in Brazilian mining lacks a set of measurement elements characteristic of the entire mining sector, focusing only on specific approaches and large corporate management.

Thus, it is understood that for QP1, the existing sustainability indicators, given their large number, scope, and flexibility in their application, reflect the possibility and feasibility of measuring the sustainability of mining in Brazil. However, the indices do not reflect this, since they are developed for certain themes and large enterprises, mineral substances, and specific regions, in addition to being composed of disproportionate indicators (in quantity, sometimes abundant, sometimes insignificant) in the dimensions of sustainability. In response to QP2, it is inferred that it is unnecessary to develop new sustainability indicators to assess mining in Brazil since there are a large number of existing indicators that possess the characteristics that allow for application in different regions. However, it is still necessary to develop indices that are capable of assessing the sustainability of Brazilian mining, because the existing international ones are directed to specific regions, with characteristics that diverge from those of Brazil, such as legislation, data availability, physical and socioeconomic aspects. Indices specifically constructed for Brazil also resulted in being very specific for certain elements, while overlooking others, making it unfeasible to apply the index.

4.2 Identification of classifications and search terms for indicators and sustainability indices in mining

A publication map can reveal the intellectual structure, thematic affinity groups and methodological emphases of an established context. This tool is based on criteria such as the occurrence of terms, study regions and bibliographic coupling of articles (CODATO, 2018). Fig. 3 shows the definition of the terms searched in the databases determined in this study. The quantitative values of the nomenclatures refer only to the data generated by Scopus. This data was used in the Vosviewer software to process and organize bibliometric information.

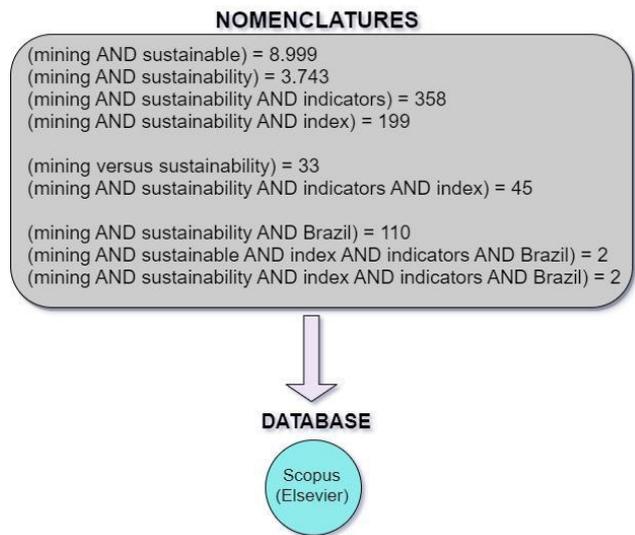


Fig. 3: Definition of the nomenclatures searched in the selected databases.

The identification of key terms in the context of mining comprised the period from 1973 to 2020. From the quantification of the occurrence of these terms in the knowledge areas of the Scopus database. Only the term "mining" does not provide the objectivity of the research, as it can arise in different contexts not connected to mineral activity. Fig. 4 shows a heat map of the terms identified in the documents collected by Scopus. In which, the hot colors (red and yellow) represent the keywords that are cited most frequently. The keywords "mining", "sustainability", "sustainable development", "heavy metals" and "data mining" formed regions in yellow connected to other terms called clusters. The clusters of the terms "data mining" and "text mining" do not comprise the scope of this work and are located in other areas of knowledge. While, the main cluster formed by terms "mining", "sustainability" and "sustainable development" contains expressions that indicate high correlation with sustainability in the mineral context.

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