SETOR MINERÁRIO BRASILEIRO E SEU IMPACTO AMBIENTAL: UMA REVISÃO DE OPÇÕES BERÇO-A-BERÇO APLICADA A RESÍDUOS, ESTÉREIS E REJEITOS

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Submetido 16/01/2020 - Aceito 24/11/2020
DOI: 10.15628/holos.2022.9413

RESUMO

O desenvolvimento sustentável torna-se urgente a partir das transformações que a sociedade contemporânea, em sua estrutura e funcionalidade, impôs à natureza, incluindo a dependência de dezenas de recursos minerais. A indústria de mineração é a base de várias cadeias produtivas e também é uma das atividades econômicas que causa mais impactos, principalmente devido à geração e destinação de resíduos e rejeitos. A exploração desenfreada de recursos, produção, consumo e a consequente geração de resíduos (cada vez mais prejudiciais e em maior escala) intensificarão a poluição (ar, solo e água), prejudicando o equilíbrio natural dos biomas. Os impactos ambientais afetam as questões econômicas e sociais de um país e, no contexto da mineração, a economia alternativa e a economia circular do berço ao berço são apresentadas como propostas inovadoras para o uso de resíduos e rejeitos. A pesquisa buscou investigar, por meio de revisão da literatura, possíveis soluções que foram desenvolvidas para o uso de resíduos de mineração, com foco no setor de mineração brasileiro. Em geral, os resíduos e rejeitos de mineração têm alto potencial para uso em outros ciclos de produção (industrial ou agrícola), o que pode contribuir para reduzir o descarte, reduzir impactos e riscos e agregar valor ao setor de mineração e às cadeias produtivas subsequentes.

PALAVRAS-CHAVE: Estéreis e rejeitos de mineração, Alternativa berço-a-berço, Economia circular, Sustentabilidade na mineração.

BRAZILIAN MINING SECTOR AND ITS ENVIRONMENTAL IMPACT: A REVIEW OF CRADLE-TO-CRADLE OPTIONS APPLIED TO RESIDUES, WASTE AND TAILINGS

ABSTRACT

Sustainable development becomes urgent from the transformations that contemporary society, in its structure and functionality, has imposed on nature, including the dependence on dozens of mineral resources. The mining industry is the basis of several productive chains and it is also one of the economic activities that causes more impacts, mainly due to the generation and disposal of waste and tailings. Rampant exploitation of resources, production, consumption and the consequent generation of waste (increasingly harmful and on a larger scale) will intensify pollution (air, soil and water), damaging the natural balance of biomes. Environmental impacts affect a country's economic and social issues, and, in the context of mining, the cradle-to-cradle alternative and circular economy are presented as innovative proposals for the applications of waste and tailings. The research sought to investigate, through literature review, possible solutions that have been developed applications of mining waste, focusing in the Brazilian mining sector. In general, mining waste and tailings have high potential for use in other production cycles (industrial or agricultural), which can contribute to reduce disposal, reduce impacts and risks, and add value to the mining sector and subsequent production chains.

KEYWORDS: Mining waste and tailings, Cradle-to-cradle alternative, Circular economy, Sustainability in mining.

1 INTRODUCTION

Although mining is indispensable for the development of any country, the exploitation and transformation of natural resources can cause environmental impacts, such as generation and disposal of waste. The production of waste is not problematic as long as it does not exceed the absorption capacity of natural cycles. However, nature no longer has the same power of regeneration as it used to have [CITATION Enr \l 1046]. On the other hand, it is observed that there are possibilities of treatment, exploitation and adequate final disposition, but there is relative inertia in the mining sector that reflects in the little (or lack of) willingness to change closed production systems (cradle to grave) to circular systems (cradle to cradle), in which waste can often be transformed into new inputs or by-products contributing to better use of resources and consequent reduction of impacts. Thus, the present work is based on the following premise: the exploitation of mineral resources and the economic development are directly associated with the environmental issue, that is, the economy cannot be sustained without the resources, and these cannot be protected when development does not consider them.

Throughout history, the environmental awareness spread worldwide, and the concept of sustainable development has emerged [CITATION Wor87 \l 1046], which translates into a new way for society to relate to its environment in order to ensure its own continuity (Bellen, 2007). Therefore, an approach to sustainability in mining should be carefully planned, covering issues such as: preservation, reduction of waste and impacts and, above all, how can the current situation be improved?

The cradle-to-cradle alternative proposes to rethink critically and reflexively the environmental issue and to create solutions that will reformulate the idea that to produce it is necessary to destroy, transforming the traditional structures of production from the cradle-to-grave, to those cradle-to-cradle. It should be emphasized that it is not only a matter of recycling, but also of the use of waste as inputs in other productive cycles to maximize value through circular economy with quality and minimum losses, without harming the natural environment and reducing impacts (McDonough and Braungart, 2002). Whether it is not possible to fully reuse the waste produced, a number of options should be considered: seek solutions in reverse logistics; use of clean energy; development of new materials; technologies; products and services that assisting in the task of recirculating; and/or reducing such residues as close to zero as possible.

The objective of this research was to discuss the environmental issue related to mining, presenting solutions of the cradle-to-cradle alternative for the reduction, treatment and recovery of waste. The specific objectives were: briefly present the Brazilian mineral production, highlighting the production chain (mineral, products, consumption, imports, exports); highpoint the production of waste and the main environmental impacts from mining activities; analyze some solutions of the cradle-to-cradle alternative aiming the reuse of waste and tailings in other productive cycles; expand the debate on waste management, environment awareness, circular economy, and sustainability in mining.

2 LITERATURE REVIEW

Mining occupies large areas for extraction of the ore, installation of equipment, machinery and structures necessary for all operational activities involved with minerals processing. In many cases, surface interventions are needed to exploit deposits that could impact the balance of the natural environment (Vieira, 2011).

The mining activity generates a great amount of waste, residues and tailings. The residues are any leftover from the research, mining or processing operations, including the inherent remains of machines or processes used, such as: tire casings, equipment parts, batteries, treatment of sewage, polluting materials, among others. The waste is all the materials generated by the exploitation activities, which are rocks considered of low economic value and generally disposed in stacks. Tailings are the substances resulting from the beneficiation processes and are usually stored in tailing dams (IPEA, 2012).

It should be emphasized that the amount of residues generated by mining activities is difficult to accurately measure because it involves complex operations and, in many cases, the inspection is precarious. In general, residues must be properly managed and disposed of, but since Brazil has few suitable waste disposal sites, in most Brazilian municipalities, residues are still being dumped. Lands, infrastructure and inspection are lacking and, in the few places suitable for disposal (stacks, dams or even properly planned landfills) the lack of monitoring hampers the waste management (Bérrios, 2010).

2.1 Mining development and the environmental issue

The evolution of humanity is closely related to the exploitation of natural resources. Records indicate that since prehistory man has used minerals: clay for the manufacture of ceramic artifacts, hard rocks for making weapons, tools and utensils, mineral ocher for rock inscriptions, among others. Over time, man has discovered many uses for different mineral resources, improved techniques for working metals and alloys, developed processes and technologies, and today society and the development of a country are extremely dependent on such resources because mining permeates them. various economic sectors ranging from utensils, construction, machinery, vehicles, energy and industrial processes to the latest technological innovations (Barreto, 2001).

Therefore, mining is a very important activity for the economic development of a country and generates several positive impacts, such as: GDP growth; job and income generation; creation of taxes and fees (e.g. in Brazil, IR - income tax, ICMS – commercial fee, CFEM – mining fee); access to international capital (mergers and acquisitions); input supply flow for the production chains (steel, construction, aluminum, among others); increased exports and formation of reserves; creation of regional development poles (exploration of deposits and expansion of local or regional infrastructure); promotion of technology development and growth in production and consumption, among others (CETEM, 2011).

On the other hand, mining activities generate a large amount of waste, waste and tailings, modify the geospatial structures of a locality, cause and/or intensify environmental impacts, damaging the natural balance of the systems (Rodovalho et al., 2019). It is noteworthy that the residues and impacts from mining do not end in the extraction and processing of a certain mineral, but it involves all related operations and also the consumption of the final product, e.g. the useful life and disposal of the products to be manufactured. from a given ore.

In general, it would be incorrect to say that only mining causes environmental impacts, as they result from various human activities, such as: unbridled exploitation of resources, agriculture, livestock, industries, construction of dams for power generation, among others. Even so, the environmental issue is one of the main problems of the sector, because the environmental impacts are divided into two categories: internal (water, air, soil, subsidence of the ground, radiation, contamination, among others); and external (climate and environmental changes, land use conflicts, depreciation of surrounding properties, generation of degraded areas, risk of accidents, imbalance of the natural environment, conflicts with the local or regional community, human health disorders, among others (Farias, 2002).

2.2 Brazilian Mineral Production and Supply Chain

Brazil has a great diversity of geological formations, which results in the presence of different ores. Brazil produces about seventy mineral substances, including metallic, non-metallic and energy minerals. Brazilian mineral reserves are strategic because they contribute to development, increase the competitiveness of production chains and attract investments to the country (Heider, 2014).

Much of the iron ore (steel raw material) production, for example, comes from Brazil, being present in the structures of buildings and in almost all appliances and electronics; gold, which has more than 75 tons produced per year in Brazil, goes far beyond jewelry and adornment, with many applications in the electronics and aerospace industries, as well as being an important regulator of the world economy; Brazilian niobium accounts for approximately 98% of world production (being used as an alloy in the production of specialty steels). The country still holds billions of tons of silicon, raw material for the manufacture of components of cell phones, computers and solar panels, among others. Aluminum is a versatile element and it is used to produce pans, cans, windows, and many others, bauxite is the aluminum ore, which Brazil accounts for almost 15% of world production. Gravel, extracted from quarries throughout the country, is a component of concrete: the basis of housing construction, buildings, roads, among others.

The Brazilian mineral extraction industry is expanding and, over the years, have been presenting positive results. These results highlight the country's participation in the world scenario with the largest reserves of niobium (98.2%), natural graphite (50.6%), tantalum (33.8%), rare earths (17.4%) and nickel. (14.7%). Other minerals also present high worldwide participation, such as: manganese, aluminum, iron, tin, feldspar, gold, zirconium, among others (13). Regarding domestic consumption, imports and exports, it is noteworthy that, although some mineral substances have higher internal consumption than production, i.e., external dependence; on the other hand, the country is one of the largest exporters of niobium, iron, kaolin, manganese, bauxite, tin, copper, nickel, gold, among others. Thus, when values (mineral production, imports and exports) are compared, they show positive trade balance (Brasil, 2016).

Some non-energy substances, especially of the metal class, are considered commodities, e.g. minerals of primary origin, necessary for the operation of various industries and which have their price regulated through international supply and demand. The main non-energy mineral commodities are aluminum, copper, tin, iron, manganese, niobium, nickel and gold. In 2015, the class accounted for more than 75% of the total value of Brazilian marketed mineral production (Brasil, 2016).

2.3 Management and handling of mining waste

In general, waste can be defined as the remains of human activities, that is, what is left, being popularly called garbage. Originally from Latin "lix", the word garbage means "everything that is useless and discarded" (Cegalla, 2005). A better definition seeks to differentiate the terms garbage and waste, garbage is the remains of human activities with no value or potential for reuse; waste is the substances that, although they are remains, still have value (social, economic and environmental), as they can be reused, recycled or transformed (Logarezzi, 2006).

Therefore, mining waste can be defined as all material resulting from the processes involved in ore research, extraction or beneficiation activities (Brasil, 2010). Broadly, such waste encompasses waste rock material and tailings, such as ore piles or debris of low economic value, rock dust, sediment, soil, shavings, sludge, wastewater slurries, leftovers from artisanal stone mining unused precious and semi-precious goods, among others, including waste materials and machinery used (IBRAM, 2016).

Generally speaking, mining waste management involves: observing current legislation and standards, studying the feasibility of reuse, geological knowledge of the area, proper disposal of waste and waste, analyzing the life cycle of the deposit, the elaboration of a safety plan, the reduction of environmental impacts, the management of gaseous emissions and monitoring of air and water quality (IBRAM, 2012). Figure 1 illustrates the theoretical life cycle planning and analysis of a deposit.

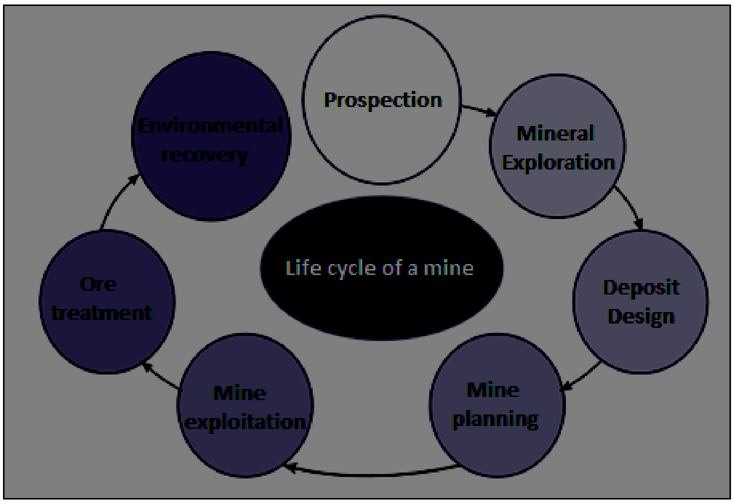

Figure 1. Flowchart of the life cycle analysis of a deposit.

Source: Adapted from IBRAM (2012).

Undoubtedly, the geological and hydrogeological knowledge of the area, allied to the prospecting planning, mineral research, deposit design, adequate operational mining processes, mineral production and beneficiation, proper waste disposal (between waste and tailings), life cycle analysis. Deposit (closure plan), security and environmental recovery plan greatly contribute to a development perspective oriented towards the preservation of natural resources, waste applications and sustainability, which can be achieved through actions that seek to maintain balance the social, political, economic, cultural and environmental aspects in order to reduce waste and impacts (Sachs, 2004). Therefore, waste rocks should be part of the planning of the operation activities of a field going beyond proper management and disposal and seeking ways to minimize environmental damage through alternative raw materials from waste and the circular economy.

One of the main challenges facing mining companies today is more than giving proper destination to the waste generated but finding viable alternatives for their use (Silveira, 2015).

2.4 Mining waste disposal

For the planning of mining waste disposal, a distinction is required between metallic and non-metallic ores, as tailings and waste generation are not equivalent. In general, non-metallic mining generates waste; while the metal one generates, in the majority, tailings (IBRAM, 2016)

In general, tailings are solid wastes that, after exhausting all treatment and recovery possibilities, are disposed of properly; waste rocks can be defined as a lithology with low economic value. The disposal of mining waste occurs through the formation of waste piles or through the containment of tailings in dams. In Brazil, both piles and dams must be constructed in accordance with safety standards established by ABNT – Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards). In Brazil, since Law number 12.305 of 2010 and the release of regulatory standards, the management practices in waste disposal sites have been adopting geotechnical and environmental safety and risk prevention criteria. These criteria also include deposit control (monitoring) and environmental recovery in the closing phase. Other practices include the reduction of piles, wastes for the topographic surface recovery, filling of depleted pits, and the use in other production cycles (Brasil, 2010; IBRAM, 2016).

Tailings disposal occurs in specific reservoirs, namely dikes or dams. Such may be from natural (conventional) soil; or constructed from the tailings themselves, it is necessary to consider the geotechnical and hydrogeological aspects and respect the established safety standards, in addition to using watertight and / or waterproofing materials to prevent seepage and/or contamination of effluents (IBRAM, 2016). Dikes and dams can be of three main types: upstream, downstream or centerline. Although the upstream method is the most used method, it needs constant monitoring, because under a saturated condition it tends to present low shear strength, and thus liquefaction (rupture) by dynamic and/or static loads (Araújo et al., 2006).

2.5 Mining and sustainability

Certainly, mineral goods are indispensable resources for the sustenance of today's society, because, directly or indirectly, they permeate and are present in all industrial sectors, having also an important participation in social, environmental, economic, political and cultural aspects. related to the development of a country. However, there is an implicit dichotomy in relating the terms: mining, development and sustainability that manifests itself from the conceptualization of the terms, that is, mining as an extraction of natural resources, renewable or not already contradicts the idea of sustainability. Although mining brings significant development, in addition to increasing the industrial sector, which in turn favors job creation and boosts the economy, it also causes social and environmental impacts and is not always aimed at mitigating its negative effects (Viana, 2012).

Other negative aspects of mining activities are the very nature of the deposits, the amount of resources available and the ability (local and global) to cope with increasingly large-scale waste generation. Ecosystems have intricate mechanisms working through the intertwining of numerous variables. Many times, when trying to solve a problem, another type of imbalance is caused (Viana, 2012; Mucci, 2005). On the other hand, the very definition of “sustainability” or “sustainable development" has undergone and continues to undergo constant reformulations, since it is not something ready and finished (absolute), but what is being practically constructed based on the interdependent relationship among society, the economy and the natural environment. In broad terms, the concept of sustainable development encompasses three main dimensions: environmental, economic and social – which is represented by Triple Bottom Line concept (Rodovalho and Cabral, 2014; Sachs, 2004; Elkington, 1998). The Triple Bottom Line is represented by an equilateral triangle that assumes the balance between the social, environmental and economic components, as shown in Figure 2.

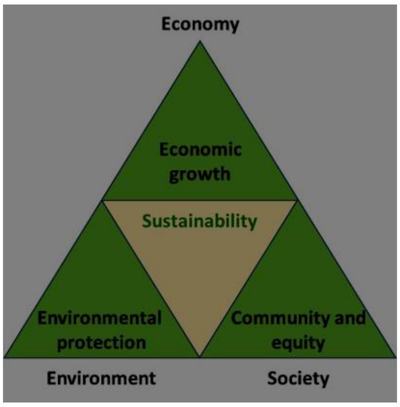

Figure 2. Sustainability explained by the Triple Bottom Line concept.

Source: Adapted from Elkington (1998).

The evolution of the concept of sustainable development is natural and desirable, as it specifically addresses a new way for society, companies and governments to relate to the environment in order to ensure the continuity of meeting their own needs (Bellen, 2007). In other words, for a company to operate in a sustainable manner, it is imperative to ensure that its operations do not result in environmental damage or contribute to any instability in the communities and economies where it operates. Sustainable development, although widespread, is still little used in the mineral sector. In general, we use more natural resources than we can replenish, and we produce more and more waste. A sustainable development policy must be premised on social and environmental responsibility in order to avoid anything that harms the natural environment (Caldeironi, 2003; Camargo, 2008).

Socioenvironmental Responsibility aims at the development of practices that promote the preservation and reduction of impacts, the recovery of degraded areas, resource exploitation alternatives and waste rocks applications, as well as the study of risks (social, economic and environmental) for evaluation of new strategies (Voltolini, 2006). Responsible companies go beyond complying with legal norms because they are really looking for sustainability in their business. In mining, the search for sustainability must be a constant understanding that it is an activity marked by the dichotomy between development and impacts and by the very nature of the need to exploit finite and depleted mineral resources, whether renewable or not.

2.6 The cradle to cradle alternative

The cradle to cradle alternative derives from and relates to the concepts of design (planning) and life cycle analysis of a product. Design should be focused on sustainability by including environmental, social and economic perspectives throughout the entire life cycle of a product during its planning (White at al., 2004). Thus, a product developed through sustainable design aims to reduce inputs, impacts and costs throughout its life cycle (Crul and Diehl, 2008). Analysis of a product's life cycle (process, input, by-product, material) encompasses its conception, development and use; it also covers the dimensions of related processes, such as: necessary facilities and equipment, maintenance and their removal and proper disposal at the end of their life spam (White at al., 2004). The life cycle assessment of a product should seek to improve the product, whenever possible, through re-design and its functional and systemic innovation. The re-design of a product implies its constant improvement or replacement of components, keeping in mind points such as the use of non-toxic materials, reverse logistics, disassembly, recycling and/or reuse (Lopes, 2012).

For this very reason, the concept of life cycle is also known by the term “cradle to grave”, where the cradle is the natural environment from which the resources to be transformed are extracted and the grave often is also the medium itself, that is, the last destination of the residues of production and consumption (Manzini and Vezzoli, 2002). Everything we produce and consume usually is incinerated, buried or disposed in dumps or landfills. The pit turns out to be the common destination for products and materials that, in most, are or become pollutants, impairing the recoverability of the natural environment (Lopes, 2012). Cradle-to-grave strategies that take into account the entire production cycle, from natural resource extraction to waste disposal, could be replaced by cradle to cradle solutions, turning waste into raw materials (Manzini and Vezzoli, 2002).

The cradle to cradle alternative proposed by Architect, Designer and Professor of Civil and Environmental Engineering at Stanford University, William McDonough and the German Chemist and Process Engineer Dr. Michael Braungart through the launch of the book “Cradle to cradle: remaking the way make things”, in 2002 (McDonough and Braungart, 2002). In Brazil, the book was published in 2014 and it presents a very simple proposal: changing the “cradle to grave” system to a “cradle to cradle” system, in which waste is (or may be, even in part) input from other cycles. The idea that waste may be the raw materials of another production cycle highlights the need to apply good design and life cycle analysis (Lopes, 2012).

There are fundamentally two types of metabolism on the planet: biological (substances that can return to nature and technical (materials that can return to industrial cycles). For example, average television is made up of thousands of products, some of which are toxic, but others are valuable to industry, and are wasted when television ends up in a landfill or dump (McDonough and Braungart, 2002). In the cradle to cradle alternative products, materials and waste must be reused as technical inputs, in the so-called technological metabolism; or return to nature as biological nutrients without polluting. Figure 3 illustrates the cradle to cradle concept.

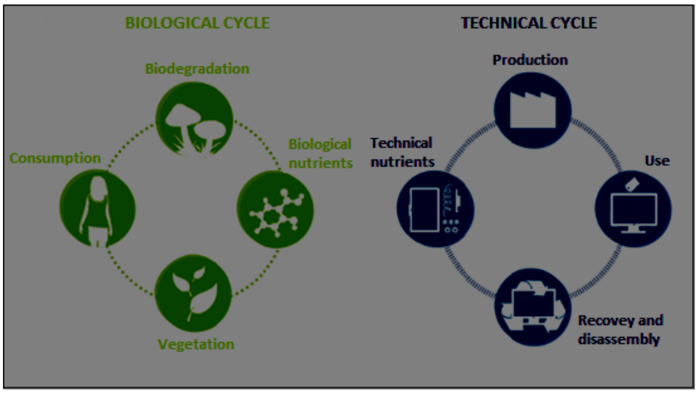

Figure 3. Cradle to cradle in the context of the circular economy.

Source: Adapted from McDonough and Braungart (2002).

3 METHODOLOGY

The methodology used for the development of the present work is the literature review, which sought to discuss the main concepts related to the proposed theme. The research also addresses the analysis of the literature regarding some ideas that have been applied in Brazil in the search for solutions for waste utilization and, consequently, reducing impacts in the mining context.

4 DISCUSSION OF THE FINDINGS IN THE LITERATURE

In this section, the techniques and Brazilian examples of exploitation of mining waste or tailings will be presented.

4.1 Exploitation of mining waste

Design, life-cycle analysis, material recycling, reverse logistics, cradle to cradle alternative, circular economy, development of new materials and technologies are relatively recent approaches. The understanding that today's waste may be tomorrow's ore is an important route for waste management in the mineral sector. Therefore, it is necessary to think about projects including the analysis of the life cycle of the deposit and the waste generated, both to reduce its generation and risks, as well as to identify new uses for them and to make better use of mineral resources (IBRAM, 2016).

There are currently several techniques being developed in a manner oriented towards the use of mining waste. In general, such proposals must comply with ABNT standards so as not to endanger human health and the natural environment, especially in the case of handling and processing of toxic materials and / or contaminants (IBRAM, 2016). Among the main techniques already in practice in the sector are:

- Agricultural use of mining waste;
- Sedimentation: technique in which the rock dust is used directly in the soil providing nutrients (calcium, phosphorus, magnesium, potassium, among others);

- Filling of depleted mine pits: practice of dumping tailings into open pit pits, in order to reduce the disposal of the dam and to avoid the need for a new dam or to increase its useful life;
- Manufacture of fertilizers, remineralizers and soil conditioners from mineral extraction and/or processing residues;
- Reduction of material losses and waste utilization in the ceramics and glass industries, metallurgy, chemistry, agriculture, among others.
- Manufacture of inputs for civil construction: Use of iron ore tailings as mixed mortar and in the manufacture of blocks (masonry) and pavers (paving).

4.2 Technologies to reduce the production of tailings and the environmental impacts

According to IBRAM (2016), several methods and technologies have also been developed to reduce and/or treat tailings, such as:

- Drained stacking: a method consisting of a drainage system that allows free water not to be retained, releasing it through a large flow internal drainage system, connected to the reservoir tailings;
- Improvements in the techniques used in the construction of tailings dams, regular monitoring and inspection, safety management plan for tailings containment structures, risk management, among others.
- Dry tailings disposal: This method called dry stacking is used for economical tailings disposal so that the tailings (generally passing through the 0.038 mm sieve) are thickened to reach thickeners. high solids content above 50%;
- Mineral filtration of concentrates and tailings that consists of the use of vacuum disc filters, promoting their filtration, and subsequently disposed in the form of dry stacking, eliminating the use of dams;
- Processing and magnetic concentration of tailings without the use of water for processing: This is the processing and magnetic concentration of tailings from the processing of tailings in the form of low iron ore piles and dams, including dry treatment. without use of water in its beneficiation. This technology has low operating cost, with full control of particulates when replacing fossil fuel with biofuel for the drying process, reducing the ecological footprint of the production chain. With this dry processing it is possible to decommission existing batteries and dams, reducing the required volume, avoiding the construction of new dams, and simultaneously eliminating the generation of their risks, among others.

4.3 Brazilian case studies

In general, the techniques of recycling and reuse of raw materials and waste are not new, just like nature that operates according to a metabolism system where waste is nutrient (McDonough and Braungart, 2002). However, in the context of mining, due mainly to the environmental and social impacts generated, the cradle to cradle alternative combined with the development of technologies that facilitate the process of waste recovery is an innovative practice that, in addition to adding value, it can make the mineral extraction industry (and its supply chains) more sustainable.

According to the data analyzed for the development of this research, it is observed that, in the context of mining, such techniques are relatively recent comprising the period marked by the last eighteen years. In Brazil, the first analysis of mining waste utilization analysis focused on filling depleted mine pits, producing fertilizers, soil improvers and remineralizers.

In 2004, a monograph developed to obtain the title of Bachelor of Geography under the guidance of Luiz Machado Filho (Professor of the Department of Ecology and Natural Resources of the Federal University of Espírito Santo) drew the attention of academia involving the areas of Geography, Environmental Engineering, Pedology, Geology, Mining Engineering and the agricultural sector. This research under the title “Rock dust utilization for fertilization of degraded soils” (Silverol, 2004) originated several new researches, including from the author herself, such as: “Harnessing mining tailings and rock alteration blankets for soil fertilization through rock dust” (Silverol, 2006), “Humifert Process for Alternative Organo-Phosphate Fertilizers: Angico dos Dias Ore Characterization of Compounds and Evaluation of Agronomic Efficiency” (MSc in Geosciences/USP)(Silverol, 2006), “Organo-Phosphate Fertilizers Produced by Humifert process: study of transformations and characterization of products” (PhD in Geosciences/USP/CNPq) (Silverol, 2010) among other research and publications. The original research had as test crop of corn and involved nine experiments with differentiated treatments, that is, three crops received no fertilizers, three received rock dust and three received conventional fertilizers. The results indicated that the rock dust used (granite and pyroxenite) has the necessary nutrients, since the corn developed satisfactorily as well as the crops treated with chemical fertilizers (Silverol, 2006). By implementing alternatives for soil fertilization, based on the use of environmentally friendly materials, we seek to promote the gradual supply of nutrients in a natural way, returning some of its characteristics, such as fertility and pH balanced that are lost with leaching, as well as giving another destination to materials with restricted use, such as rock dust (Silverol, 2006).

The paper presented at the 49th Brazilian Congress of Ceramics under the title: “Study of the potentiality of kaolin and granite residues for the production of ceramic blocks” is a practical research that shows the potential use of residues from beneficiation of kaolin and granite for application in ceramic masses and for the production of ceramic blocks (Ramalho et al., 2005).

At the II Geojovem - Brazilian Symposium of Young Geotechnical Engineers - the work entitled “Using a Mining Tailing as an Alternative for Stabilization of a Midwestern Tropical Soil” was presented and it presented a laboratory investigation covering a lateritic soil of the Federal District and an iron ore tailings from the state of Minas Gerais. The iron ore tailing used in the experiment consisted of a typically sandy (granular) sample. The tests involved a thorough analysis according to ABNT requirements, including the determination of the specific grain mass, particle size analysis, mini-compression and simple compression tests and determination of the maximum and minimum void indices, performed at the UnB Geotechnical Laboratories (University of Brasilia). The results obtained in the compression tests show an increase in the simple compressive strength values when a 25% percentage of soil tailings was added and practically doubled when the tailings and soil percentages were equal. The research presents a viable possibility of reducing the impacts associated with tailings disposal, because the tailings can be used in construction paving equipment (Gratão, Pereira and Ribeiro, 2006).

The results of the work entitled “Utilization of white ceramic kaolin residue” showed that it is technically possible to replace raw material from the white ceramic industry with kaolin residue (Souza, 2007). The research “Use of mineral residues in the formulation of mortars for civil construction” demonstrated the feasibility of partially replacing cement with mining residues to produce mixed mortars (Santos, 2008).

Since 2010, Reciclos-CNPq (Solid Waste Research Group of the Federal University of Ouro Preto - UFOP) has been conducting research on methods to reuse mining waste. Due to the diversity and complexity of the research developed, it would be practically impossible to analyze each one of them. In general, the works developed have been presenting positive results and have even received awards in innovation and sustainability events. Among the main projects developed, one should be highlighted: the project "Sustainable Pavers with Iron Ore Dam Tailings" deals with the application of iron ore dam tailings as input for civil construction and road infrastructure. The research began in 2010 with the project "Reuse of solid waste from mineral based industry as a matrix for the production of concrete and mortar". As a result, it was found that in addition to the production of mortars, the production of tailing pavers is a viable alternative for reducing environmental liabilities. This project involved the production of prefabricated (in-situ cast) concrete artifacts from aggregates taken from dam tailings. In the stress tests it was found that the pieces can perform structural function, provided that the addition does not exceed the limit of 80% in relation to the natural aggregates of Portland Cement matrices. The experimental results were used in pilot scale, in an industrial plant certified by ABCP (Brazilian Portland Cement Association). The artifacts were technologically tested and showed good results (Silva at al., 2011; Peixoto, 2016). Figure 4 illustrates the pavers produced from iron ore tailings.

Figure 4. Paver with ferrous tone compared to a conventional one.

Source: Silva et al. (2011).

Among the works produced in the area by Unifal-MG– Federal University of Alfenas, in the Poços de Caldas advanced campus, the monograph entitled “Utilization of radioactive waste generated in the extraction of rare earths from monazitic sand” deserves mention. Generally associated with elements such as thorium and uranium, monazite processing generates waste containing such radioactive materials. As conclusions, the research allowed the analysis of methods used for the extraction of radioactive elements (thorium and uranium) from the liquid waste from the processing of monazitic sand for extraction of the rare earth element. The Amex (amine extraction) process uses solvents for the re-extraction of these elements which, besides avoiding damage to the environment, generates other by-products that can be used in industry. The procedure is of fundamental importance, as it minimizes the environmental impacts generated, since radioactive waste is difficult to dispose of, in order to preserve the environment and living beings. In addition, in the extraction of radioactive elements there is also rare earth elements re-extraction, which increases the processing efficiency of monazite. Thorium and uranium, if purified, may also serve other technological applications (Barato, 2015). El Hajj et al. (2019) presents the study of reuse options for a niobium mine waste that shows low to moderate activity concentrations of radioisotopes that was also led by Unifal-MG in partnership with IPEN – Institute of Energy and Nuclear Research.

Finally, the recent article presented at the VI Day of the Institutional Capacity Building Program - PCI/CETEM entitled “The Circular Economy and the Role of Mining” addresses the concept cradle to cradle broadly in the context of mining and its productive chains. Circular economics (EC) is a viable alternative to improving resource use while reducing impacts. As mining is at the base of supply chains, the CE aims to integrate costs and value into the environment and resources by proposing a system where materials and waste circulate for as long as possible through supply chains (Duthie and Lins, 2017).

In general, the review shows different possibilities of mining waste utilization. Waste rocks has high potential for agricultural uses both in the production of fertilizers and in more complex studies involving the ability of soil correction and recovery; as for the tailings, being one of the main causes of environmental impacts, it is evident that, besides the real possibility of utilization (mixed mortars, block and pavers manufacture, among others), there can also be a consequent reduction of their disposal, reducing the risk of accidents (dam rupture) since the tailings are periodically removed to be reused. In addition, the proposal may generate greater value across production chains, as different types of industries may benefit from such wastes, including mining companies themselves.

5 FINAL CONSIDERATIONS

The premise that the cradle to cradle alternative, the circular economy and the waste utilization can bring more sustainability to the mining sector and to their supply chain was corroborated by examples shown in this article. As the mineral extraction industry is the basis of several production chains, it would be utopian to think of total sustainability or sustainable development. However, new waste rocks applications (even only part of it) can contribute to reducing disposal, minimizing impacts and risks, and promoting better use of resources and new inputs. On the other hand, production chains can also benefit from waste utilization through alternative inputs (technical or biological nutrients), circular economy and industrial symbiosis.

It is possible to think of a future where various engineering and reengineering will work hand in hand with corporate social and environmental responsibility to develop new technologies, to better use resources and waste, and for the preservation of the natural environment and life itself. The cradle to cradle alternative proposes that the project, design and selection of materials should be in line with the objectives outlined in the circular economy context, e.g. better use of inputs, materials, processes and waste. Moreover, at the end of the life cycle, the type of metabolism desired for the waste should be biological or technological. Hence, it is necessary:

- Create a “positive passive” list and always seek innovative components and materials from waste utilization;

- Activate the "positive passive" list: stimulate the circular economy and industrial symbiosis by changing paradigms, adding value to business and effectively contributing to the best use of resources and consequent reduction of impacts;
- Innovate and reinvent: do not be content to minimize impacts; seek to create ever more innovative products and materials that will feed the technology cycle or generate nourishing effects on the environment.

Finally, it is suggested to broaden the debate about the environmental issue to the development of new ideas, processes, materials and technologies aimed at the use of waste in the context of mining and its production chains.

6 REFERÊNCIAS

ARAÚJO, G. C., BUENO, M. P. B., SOUSA, A. A., MENDONÇA, P. S. M. Sustentabilidade empresarial: Conceito e Indicadores. III CONVIBRA. 24 a 26 de novembro de 2006.

BARATO, T. Aproveitamento de resíduos radioativos gerados na extração de Terras Raras a partir de areia monazítica. Trabalho de Conclusão de Curso (Engenharia Química) - Universidade Federal de Alfenas – UNIFAL, Instituto de Ciência e Tecnologia – ICT. Poços de Caldas, MG, 2015.

BARRETO, M. L. Mineração e desenvolvimento sustentável: Desafios para o Brasil. Rio de Janeiro: CETEM/MCT, 2001.

BELLEN, H. M. V. Indicadores de sustentabilidade: uma análise comparativa. 2ª ed. Rio de Janeiro: FGV, 2007.

BÉRRIOS, M. R. Riscos apresentados pelos aterros de resíduos sólidos em áreas de rede urbana densa no Brasil. VI Seminário Latino-Americano de Geografia Física, II Seminário Ibero-Americano de Geografia Física. Universidade de Coimbra, maio de 2010.

BRASIL. Lei nº 12.305 de 02 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos.

______. Departamento Nacional de Produção Mineral - DNPM. Anuário Mineral Brasileiro: Principais Substâncias Metálicas. (Coord. Geral Wagner F. Pinheiro, Osvaldo B. Ferreira Filho, Carlos Augusto Ramos Neves; Equipe Técnica por Marina M. Dalla Costa et al.). Brasília: DNPM, 2016.

BRUNDTLAND, G. H. (org.). Nosso futuro comum. São Paulo: FGV, 1991. (WCED: Our Common Future. (Oxford: Oxford University Press, 1987).

CALDEIRONI, S. Os bilhões perdidos no lixo. 4ª ed. São Paulo: Humanitas, 2003.

CAMARGO, A. Governança para o século 21. In: TRIGUEIRO, A. (Coord.). Meio Ambiente no século 21: 21 especialistas falam da questão ambiental nas suas áreas de conhecimento. 5ª ed. Campinas: Armazém do Ipê, 2008.

CEGALLA, D. P. Dicionário Escolar da Língua Portuguesa. São Paulo: Companhia Editora Nacional, 2005.

CETEM. Centro de Tecnologia Mineral. Ministério da Ciência, Tecnologia e Inovação (MCTI). Recursos Minerais & Sustentabilidade Territorial: grandes minas (Vol. 1). Francisco R. C. Fernandes, Maria Amélia R. S. Enríquez, Renata C. J. Alamino (Eds.). Rio de Janeiro: CETEM/MCTI, 2011.

CRUL, M.; DIEHL, J. C. Design for Sustainability (D4S): Manual and Tools from Developing Countries - 7th Annual ASEE Global Colloquium on Engineering Education. Cidade do Cabo, África do Sul, 2008.

DUTHIE, A. C. R.; LINS, F. A economia circular e o papel da mineração. VI Jornada do Programa de Capacitação Institucional - PCI/CETEM - 21 de setembro de 2017.

EL HAJJ, T. M.; GANDOLLA, M. P. A.; SILVA, P. S. C.; TORQUATO, H.; DELBONI JR., H. Long-term prediction of non-processed waste radioactivity of a niobium mine in Brazil. Journal of Sustainable Mining, p. 142-149, 2019. Doi: https://doi.org/10.1016/j.jsm.2019.04.003

ELKINGTON, J. Cannibals with Forks: The Triple Bottom Line of the 21st Century Business. The Conscientious Commerce Series, 1998.

FARIAS, C. E. G. A mineração e o meio ambiente no Brasil. Relatório Preparado para o Centro de Gestão e Estudos Estratégicos – CGEE. Programa das Nações Unidas para o Desenvolvimento – PNUD. Contrato 2002 /001604, 2002.

GRATÃO, L. S.; PEREIRA, E. L.; RIBEIRO, L. F. M. Utilização de um rejeito de mineração como alternativa para estabilização de um solo tropical da região Centro-oeste. Anais... (COBRAMSEG/SBMR/GEOJOVEM), 2006.

HEIDER, M. Valorizando as reservas minerais do Brasil. Revista: In the mine, 18 de dezembro de 2014. Available at: https://www.inthemine.com.br/site/valorizando-as-reservas-minerais-do-brasil/.

IBRAM. Gestão para a sustentabilidade na mineração: 20 anos de História. IBRAM, 2012.

______. Instituto Brasileiro de Mineração. Gestão e Manejo de Rejeitos da Mineração. IBRAM, 2016.

IPEA. Instituto de Pesquisa Econômica Aplicada. Diagnóstico dos Resíduos Sólidos da Atividade de Mineração de Substâncias Não Energéticas: Relatório de Pesquisa. Brasília: IPEA, 2012.

LEFF, E. Racionalidade Ambiental: a reapropriação social da natureza. Civilização Brasileira, 2006.

LOGAREZZI, A. Educação ambiental em resíduo: uma proposta de terminologia. In: Consumo e Resíduo: fundamentos para o trabalho educativo. São Carlos: EdUFSCar, 2006.

LOPES, P. P. Desenvolvimento sustentável: a nova revolução industrial através da alternativa berço a berço. Trabalho de conclusão de curso (Administração), Universidade do Vale do Sapucaí – UNIVÁS, Pouso Alegre, MG, 2012.

MANZINI, E. ; VEZZOLI, C. O Desenvolvimento de Produtos Sustentáveis. São Paulo: USP, 2002.

MCDONOUGH, W.; BRAUNGART, M. Cradle to Cradle: remaking the way we make things. New York, North Point Press, 2002.

PEIXOTO, R. A. F. Utilização de rejeitos de barragens de minério de ferro na construção civil. 2016. Relatório de Pesquisa em Ciência, Desenvolvimento e Tecnologia para aplicação de Rejeitos de Barragens de Minério de Ferro como fração inerte para matrizes de cimento Portland em obras de Infraestrutura e Construção Civil, 2016.

RAMALHO, M. A. F., ALMEIDA, R. R., NEVES, G. A., SANTANA, L. N. L. Estudo da potencialidade de resíduos de caulim e granito para produção de blocos cerâmicos. Anais do 49º Congresso Brasileiro de Cerâmica, 6 a 9 de junho de 2005, São Pedro, SP.

RODOVALHO, E. C., CABRAL, I. E. 2014. Estimate of hourly productivity applied to elaboration and implementation of mining plans. *REM. Revista Escola de Minas*, **67**, (2), 221–227. http://dx.doi.org/10.1590/S0370-44672014000200015

RODOVALHO, E. C., PASSOS, A. O. P., DE TOMI, G., TENÓRIO, J. A. S. 2019. Sequential glory hole approach as a new mining method for sustainable operations. *Journal of Materials Research and Technology*, **8**, (5), 4788 - 4796. (https://doi.org/10.1016/j.jmrt.2019.08.025).

SACHS, I. Desenvolvimento: Includente, sustentável, sustentado. Rio de Janeiro: Garamond, 2004.

SANTOS, M. L. L. de O. Aproveitamento de resíduos minerais na formulação de argamassas para a construção civil. Tese (Doutorado em Ciência e Engenharia de Materiais) - Universidade Federal do Rio Grande do Norte, Natal, RN, 2008.

SILVA, M. J., NUNES, T, ALMADA, S., ALVES, V. J. G., PEIXOTO, R. A. F., BEZERRA, A. C. S. Pavimentos Sustentáveis – Análise de viabilidade técnico econômica para fabricação de blocos de concreto para pavimentos permeáveis. Publicações Reciclos/CNPq - UFOP. Anais do 53º Congresso Brasileiro do Concreto – CBC, 2011.

SILVEIRA, M. D. Utilização de resíduos da mineração na construção civil. Monografia (Especialização em Construção Civil) - Escola de Engenharia da Universidade Federal de Minas Gerais. Belo Horizonte: UFMG, 2015.

SILVEROL, A. C. Rochagem: Aproveitamento de pó de rocha para recuperação e fertilização de solos (Graduação em Geografia) - Universidade Federal do Espírito Santo (Orientador: MSc. Luiz Machado Filho). Vitória: EDUFES, 2004.

SILVEROL, A. C. Aproveitamento de rejeitos da mineração e mantos de alteração de rochas para fertilização de solos através da técnica de rochagem. GEOGRAFARES, nº 5, p. 7-16, 2006.

SILVEROL, A. C. Processo Humifert para fertilizantes alternativos organo-fosfatados: obtenção a partir do minério de Angico dos Dias, caracterização dos compostos e avaliação da eficiência agronômica (Mestrado em Geociências, Geoquímica e Geotectônica) – Universidade de São Paulo, (Bolsista do (a) Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, sob a Orientação da Profa. Dra. Maria C. M. de Toledo). São Paulo: USP/CAPES, 2006.

SILVEROL, A. C.; MACHADO FILHO, L. Utilização de pó de granito e manto de alteração de piroxenito para fertilização de solos. Revista Brasileira de Agroecologia, v. 2, p. 703-707, 2007.

SILVEROL, A. C.; TOLEDO, M. C. M. Processo Humifert: fabricação de compostos fertilizantes organo-fosfatados através de rocha fosfática e resíduos orgânicos. In: MILORI, D. M. B. P.; MARTIN-NETO, L.; SILVA, W. T. L.; MARCONCINI, J. M.; BERTUCCI-NETO, V. (Org.). Caracterização, Aproveitamento e Geração de Novos Produtos de Resíduos Agrícolas, Agroindustriais e Urbanos. 1ª ed. São Carlos: Embrapa, 2010, v. 1, p. 13-18.

SILVEROL, A. C. Fertilizantes organo-fosfatados produzidos pelo processo Humifert: Estudo das transformações e caracterização dos produtos. Universidade de São Paulo (Doutorado em Geociências). (Bolsista do (a): Conselho Nacional de Desenvolvimento Científico e Tecnológico, CNPq, Brasil), Estágio de doutorado no exterior (PDEE/CAPES) na Lincoln University, Canterbury, Nova Zelândia. (Orientador em Lincoln University: Prof. Dr. Leo M. Condron com Profa. Dra. M. Cristina Motta de Toledo (USP/CNPq, Brasil), 2010.

SILVEROL, A. C.; CONDRON, L.M.; TOLEDO, M. C. M. . Evaluation of phosphorus forms in an organo-phosphate fertilizer. In: 19th World Congress of Soil Science, 2010, Brisbane. Proceedings, 2010.

Silverol, A. C.; TOLEDO, M. C. M.; SILVA, W. T. L. Neoformação de fosfato de cálcio e comportamento da solubilização do fósforo no processo Humifert. (Pós-Doutorado em Nanotecnologia aplicada ao agronegócio pela Embrapa Instrumentação Agropecuária, EMBRAPA CNPDIA, São Carlos, SP (2012-2013). Bolsista/CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, Brasil). Revista do Instituto Geológico, v. 34, p. 45-56, 2013.

SOUZA, L. L. Aproveitamento de Resíduos de Caulim em Cerâmica Branca. Dissertação (Mestrado em Engenharia Mecânica). Universidade Federal do Rio Grande do Norte. Natal, RN, 2007.

VIANA, M. B. Avaliando Minas: índice de sustentabilidade da mineração (ISM). 2012. 372 p. Tese (Doutorado em Desenvolvimento Sustentável) - Universidade de Brasília – UNB. Brasília: UNB, 2012.

VIEIRA, E. A. A (In) sustentabilidade da indústria da mineração no Brasil. Estação Científica (UNIFAP). Macapá, v. 1, n. 2, p. 01-15, 2011.

MUCCI, J. L. N. Introdução às ciências ambientais. In: PHILIPPI JR, A.; PELICIONI, M. C. F. Educação ambiental e sustentabilidade. USP- Editora Monole Ltda - SP, 2005.

VOLTOLINI, R. Modelos e ferramentas de Gestão Ambiental: Desafios e perspectivas para as organizações. Alcir Vilela Júnior, Jacques Demajorovic. São Paulo: SENAC, 2006.

WHITE, P., ST PIERRE, L., BELLETIRE, S. Okala learning ecological design. Portland, US, IDSA, 2004.

COMO CITAR ESTE ARTIGO:

Lopes, P. P., Rodovalho, E. da C., & Mohamad El Hajj, T. (2022). Brazilian mining sector and its environmental impact: a review of cradle-to-cradle options applied to residues, waste and tailings. HOLOS, 6. Recuperado de https://www2.ifrn.edu.br/ojs/index.php/HOLOS/article/view/9413

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Editor(a) Responsável: Francinaide de Lima Silva Nascimento
Pareceristas *Ad Hoc*: Dr. Andre Cezar Zingano

Recibido: 16 de Janeiro de 2020

Aceito: 24 de Novembro 2020

Publicado: 28 de Dezembro de 2022