



Carbon footprint of solid waste from iron ore mining: a Brazilian case study

A pegada de carbono dos resíduos sólidos da mineração de ferro: um estudo de caso no Brasil

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Article received on June 11, 2021, final version accepted on March 14, 2022, published on September 6, 2023.

ABSTRACT: Actions to mitigate climate change aimed at reducing CO₂ emissions by the most prevalent sectors of the market are essential for the sustainable development of society. Iron ore mining is a protagonist of the Brazilian economy; however, the activity is associated with high CO₂ emissions and Solid Waste (SW) generation, which represent major challenges for the sector. In this context, the aim of this study was to evaluate and discuss the SW management Carbon Footprint at “Mina do Andrade”, an iron ore mining company located in the northeastern region of the Iron Quadrangle region (MG/BR), as an instrument for the development of low carbon policies. This assessment was carried out using the Composite Method of Current Accounts (MC3), which allows estimating the Corporate Carbon Footprint (CCF) of organizations based on documents provided by the company itself. The total emissions (net CCF) for SW management in the company were 346.58 tCO₂ in 2017, 343.15 tCO₂ in 2018 and 343.44 tCO₂ in 2019. The total Industrial Solid Waste (ISW) CCF was zero throughout the period, as the forest areas contained within the boundaries of the company supplied the demand for carbon sequestration generated in the waste management. The reduction in ISW generation and the adoption of cleaner production strategies were the main drivers for the reduction of gross carbon emissions by the company in the three-year period under evaluation. The use of land for the disposal of waste rock in piles generated the highest SW CCF of the company in the entire evaluation period. So, this study is pioneer in the evaluation of the SW CCF of iron ore mining, and fills part of the existing gap due to the scarce number of peer-reviewed studies regarding the sector's Carbon Footprint.

Keywords: carbon footprint; compound method based on financial accounts (MC3); mining; mining waste.

RESUMO: Ações para mitigação das mudanças climáticas que visem à redução das emissões de CO₂ pelos setores mais prevalentes do mercado são indispensáveis para o desenvolvimento sustentável da sociedade. A mineração

de ferro é uma protagonista da economia brasileira, contudo a atividade está associada a altas emissões de CO₂ e geração Resíduos Sólidos (RS), que representam grandes desafios para o setor. Neste contexto, o objetivo deste estudo foi avaliar e discutir a Pegada de Carbono do manejo de RS na Mina do Andrade, um empreendimento de mineração de ferro localizado na região nordeste do Quadrilátero Ferrífero (MG/BR), como instrumento para desenvolvimento de políticas de baixo carbono. Essa avaliação foi feita por meio do Método Composto das Contas Correntes (MC3), o qual possibilita a estimativa da Pegada de Carbono Corporativa (PCC) de organizações a partir de documentos fornecidos pela própria empresa. As emissões totais (PCC líquida) para o manejo de RS no empreendimento foram de 346,58 tCO₂ em 2017, 343,15 tCO₂ em 2018 e 343,44 tCO₂ em 2019. A PCC total dos Resíduos Sólidos Industriais (RSI) foi nula em todo o período, visto que as áreas de florestas contidas nos limites do empreendimento supriram demanda por sequestro de carbono gerados no manejo dos resíduos. A redução na geração de RSI e a adoção de estratégias de produção mais limpa foram os principais propulsores para a redução da emissão bruta de carbono pelo empreendimento no triênio avaliado. O uso do solo para a disposição dos estereis de mineração em pilhas gerou a maior PCC de RS do empreendimento em todo o período avaliado. Então, este estudo, pioneiro no estudo da PCC de RS da mineração de ferro, preenche parte da lacuna existente devido ao escasso número de estudos revisados por pares a respeito da Pegada de Carbono do setor.

Palavras-chave: pegada de carbono; método composto das contas correntes (MC3); mineração; resíduos de mineração.

1. Introduction

The use of fossil energy and changes in land use have been triggering an increase in the carbon dioxide (CO₂) concentration in the atmosphere (Canadell et al., 2007), which is altering the energy dynamics of the planet's climate system, causing an increase in air temperature (Hansen et al., 2010; Cubasch et al., 2013; Dai, 2016). Such climate changes have the potential to trigger a series of negative impacts on terrestrial and aquatic ecosystems (Lindner et al., 2010; Doney et al., 2012), consequently influencing economic systems and human well-being and health (Wheeler & Von Braun, 2013; Urry, 2015; Pecl et al., 2017). So, the search for strategies aimed at reconciling socioeconomic development and environmental integrity maintenance has become a central issue for modern society.

The perception of human co-responsibility for climate change on the planet has driven efforts

to develop international climate policies and agreements, such as the current Paris Agreement (Falkner, 2016). With increasing pressure from foreign policies and public awareness, many institutions began to account, control and report on their carbon emissions. In Brazil, industrial processes were responsible for about 5% of carbon emissions in the country between 1990 and 2019 (SEEG, 2021a), and, among the emissions generated by industrial processes, approximately 33% were generated by mining, which corresponds to an approximate emission of 677 Mi tons of CO₂ in that period (SEEG, 2021b). So, the mining industry, one of the protagonists of the Brazilian economy, is evident as a priority target of strategies to mitigate the impacts of global warming in the country (Farjana et al., 2018).

The state of Minas Gerais (MG) concentrates a large part of Brazil's mineral wealth, especially iron ore. In 2018, MG was the largest iron ore producer in the country, generating revenue

of approximately BRL 36 billion (ANM, 2020). This context indicates the importance of the iron mining industry in MG for the national socio-economic sphere. In the last estimate of greenhouse gas emissions made for the state of Minas Gerais, in 2014, the mining sector had been responsible for the emission of 0.85 million tons of CO₂, approximately 39% of the carbon dioxide production by the industrial sector in the state (FEAM, 2016a). According to FEAM (2018a; 2018b), the total Solid Waste (SW) inventoried in the industrial sector of the state of Minas Gerais, in 2017, was approximately 600 million tons, among which, about 90% had origin in metallic mineral mining activities. In this way, this sector faces major challenges of effective governance systems in the sustainability scope, since the socio-environmental risks from the mining activity can generate negative impacts on ecosystems, associated with direct and indirect CO₂ emissions, including those derived from the management of large SW volumes in mineral production (Farjana et al., 2019). Therefore, the commitment of the sector with sustainable development is an urgent condition for its perpetuation.

In this article, the Compound Method of Current Accounts (MC3) and the methodology to estimate the Corporate Carbon Footprint (CCF) are applied to “Mina do Andrade”, an iron ore mining company used as a case study for estimating and understanding the Solid Waste (SW) management carbon footprint of mining projects. The results of the monthly SW CCF generated in the mine, composed of Industrial Solid Waste (ISW) and Mining Waste (MW) that are characterized as sterile, are presented for the years 2017, 2018 and 2019, followed by the discussion of sustainability aspects. Thus, this work aimed to evaluate and discuss the

SW management CCF at the “Mina do Andrade” company and contribute to discussions about CO₂ emissions in mining projects and sustainable solutions for this environmental liability.

2. Materials and methods

2.1. Characterization of the study area

“Mina do Andrade” is a mining company of the Arcelor Mittal Brazil group located in the State of Minas Gerais/ Brazil (19°47'02.51" S/ 43°09'10.83" W), in the northeastern region of the Iron Quadrangle region. The main ore exploited in its deposits is hematite, an iron oxide (Fe₂O₃), which is mined in the open and sent to a Run Of Mine square (ROM), where the ore processing is simple and dry using crushers and vibrating screens. “Mina do Andrade” has territorial extension of 2696.81 ha, of which 85% are occupied by native vegetation in different successional stages and preservation levels.

From January 2018, the company underwent a restructuring process of the waste environmental policy aimed at increasing the socio-environmental SW management efficiency. The main strategies adopted include: encouraging recycling, reuse and reverse logistics; waste recovery; better mapping and distribution of dumps; regularization of environmental licenses; regularization of the solid waste management plan and the health services waste management plan; regularization of the waste transport manifest and related documents; regularization of the emergency action plan; regularization of the federal technical register of potentially polluting activities and/or users of environmental resources and the federal technical register of activities and

instruments of environmental defense; and the reduction of costs with waste disposal. At the same time, in November 2018, the company started the Itabirite Project (IP), which aimed at building an itabirite concentration plant, previously economically unfeasible, whose work was completed in December 2019. This project aimed to increase the quality of the ore produced, generating a positive impact on costs and increasing the useful life of the mine.

Throughout the company, hazardous and non-hazardous Industrial Solid Waste (ISW) are generated, which have different origins and final destination processes (Table 1), and Mining Waste (MW), which is divided into two categories: barren waste rock and compact waste rock, which are deposited in Waste Piles (WP). Barren waste rock is generally composed of quartzites, schists and other non-economically viable minerals; while compact waste rock consists of itabirite (a mineral with iron content between 50% and 55%), and was considered temporary sterile before 2020. In 2017, 2018 and 2019, the company had two active WPs and two inactive WPs, which occupied total area of 94.58 ha. It is important to emphasize that, over the study years (2017, 2018 and 2019), the area occupied by the four WPs was constant, only varying their growth in height.

2.2. The Compound Method based on Financial Accounts (MC3)

Considering that mining and ore processing are major sources of Greenhouse Gas (GHG) emissions, studies that assess these emissions can

contribute to their reduction in order to meet climate change mitigation goals (Gan & Griffin, 2018). Direct or indirect CO₂ emissions (associated with the consumption of energy, goods and services by the company) can be assessed using the Carbon Footprint guided by Life Cycle Analysis (LCA) (Gan & Griffin, 2018), which basically consist of inventorying a company's resource consumption data (goods and energy) and translating them into CO₂ emissions.

For this study, a Hybrid Approach (HA) for LCA was used, the “Compound Method of Current Accounts” (MC3), which integrates “bottom-up” and “top-down” LCA analysis, being simple to be performed and presenting more complete results, including information that would normally not be individually represented by these analyses (Crawford et al., 2018). The MC3 is a method for estimating the Corporate Carbon Footprint (CCF) applicable to all types of companies, at different scales, categorized as HA, and which provides a more accurate and faster assessment of the gases emitted, in addition to easier to understand results (Alvarez & Rubio, 2015; Crawford et al., 2018).

Doménech Quesada (2006) points out that the CCF is an instrument that allows companies to plan strategies to reduce GHG emissions and to combat climate change. In view of this, MC3 proves to be the most appropriate method to achieve the aim of estimating and discussing the CCF of Industrial Solid Wastes (ISW) and Mining Wastes – waste rock (MW) from an iron ore mining company in MG, as a tool to the promotion of low carbon policies in the sector.

TABLE 1 – Solid Industrial Waste Generated at the “Mina do Andrade” mine in the years 2017, 2018 and 2019, classified according to ABNT NBR 10004 (ABNT, 2004).

Classificação (ABNT 2004)	Types of ISW
Hazardous waste (Class I)	Printer cartridges and copier toners; paint waste; waste solvents, lubricants; used oil and grease residues; filters contaminated with oily residue; material contaminated with hydrocarbon; electrode tip; gloves contaminated with oily residue; ambulatory waste; fluorescent/incandescent light bulbs; cells, batteries; contaminated sawdust, contaminated soil; contaminated PPE.
Non-hazardous non-inert waste (Class IIA)	Rubber; gloves, boots, non-contaminated uniforms; sanitary effluent, toilet paper; styrofoam packaging; disposable cups; napkins, toothpicks; food leftovers; cement bags; electrode tip; cutting disk; and all others that do not fall under the hazardous or hazardous inert SW classifications.
Inert non-hazardous waste (Class IIB)	Wood; paper/cardboard, plastic; scrap metal, cans; earth, soil; glasses; PVC scrap; helmets, goggles; blasting slag; aluminum foils; cutting and grinding disks; electrical wires; staples, nails, screws; plaster, excavation residue.

SOURCE: the authors.

2.2.1. Estimating the industrial solid waste corporate carbon footprint

Monthly assessments of the SW management CCF at “Mina do Andrade” were carried out for the years 2017, 2018 and 2019. CCF estimate of the final ISW destination (most common non-hazardous and hazardous waste, including discharges into sanitation networks), was based on the concepts and principles of Domenéch Quesada (2006) and on standards and systematization of MC3 V2.0 by Domenéch Quesada et al. (2010) and Marañón et al. (2008). According to MC3 V2.0, in order to estimate ISW CCF, CO₂ emissions that are no longer absorbed by the forested areas that are being demanded for carbon sequestration generated by waste management must be calculated. Therefore, to estimate the gross ISW CCF, CO₂ sequestration factor of 3.66 tCO₂/ha used in MC3 V2.0 (Coto-Millán et al., 2008) was adopted, the conversion factors of the “CO₂-absorbing forests” category proposed by Marañón et al. (2008) ($F_{con_{for}}$) and the productivity

factor for Brazilian forests proposed by the Global Footprint Network (GFN) (2019) (PF_{for}), according to **equation 1**. The conversion factors proposed by Marañón et al. (2008) allow the conversion of mass (in tons) of several ISW categories generated in a company into biologically productive areas (in hectares) necessary for its final destination. To this end, data on energy and matter consumed are used for the final disposal of each ISW category. It is important to point out that the conversion factor proposed by Marañón et al. (2008) does not include the impacts generated by the transport of waste, and this footprint must be included in the service footprint of the generating company or the company responsible for transport (Marañón et al., 2008).

$$CCF_i = P_i * F_{con_{for}} * PF_{for} * 3.66 \quad (1)$$

SUBTITLE: where P_i refers to the amount of ISW “i” generated, in tons; $F_{con_{for}}$ refers to the Conversion Factor for forested areas; and, PF_{for} refers to the Productivity Factor of forested areas.

The estimate of the net ISW CCF was made from the subtraction between the gross ISW “i”

CCF and its counter-footprint ($cfco_{2i}$), which was determined from equation 2. The counter-footprint basically consists of forested areas within the boundaries of the company.

$$cfco_{2i} = P_i * c f_i * a_{for} * PF_{for} * 3.66 \quad (2)$$

SUBTITLE: where, $c f_i$ is the conversion factor for estimating the counter-footprint of ISW "i" proposed by Marañón et al. (2008); and a_{for} refers to the percentage of the company's forested area.

The net total ISW CCF was estimated from the sum of partial CCF of each waste "i" according to **equation 3**:

$$CCF = \sum_i CCF_i \quad (3)$$

2.2.2. Estimating the mining waste corporate carbon footprint

MC3 V2.0 does not include the estimation of the mining waste carbon footprint. Thus, in view to obtaining a more realistic estimate of the CCF generated by SW management at "Mina do Andrade", this work was proposed and used an adaptation of the "land use" methodology of MC3 V2.0, which assumes that the "footprint due to occupation of bioproductive spaces [...] will have footprint equivalent to the space occupied (forest, cropland, pasture or sea)" (Doménech Quesada et al., 2010, p. 121). That is, the CCF generated by mining waste is equivalent to the carbon sequestration deficit generated by the suppression of vegetation for the installation of WPs. So, the estimation of the waste CCF was performed from the area occupied by the base of

the waste piles and the carbon absorption factor (Coto-Millán et al., 2008), according to **equation 4**:

$$PCC_{waste\ pile} = A * PF_{for} * 3.66$$

SUBTITLE: where A indicates the base area of waste piles.

2.2.3. Data collection and analysis

Data for estimating SW CCF at "Mina do Andrade" were collected from documents provided by the company itself, which include: Solid Waste Inventory; Waste Monitoring Record; Solid Waste Management Plan (PGRS); Health Service Waste Management Plan (PGRSS); Rural Environmental Registry (CAR); and Standards Report.

Data obtained were organized in order to facilitate the CCF calculation, and ISW generated at "Mina do Andrade" were classified according to the MC3 V2.0 methodology (Marañón et al., 2008; Doménech Quesada et al., 2010). The classification was based on the type of management of each waste, as proposed by Marañón et al. (2008)1. Subsequently, a spreadsheet was developed in Microsoft® Office Excel software, in order to adapt the spreadsheet proposed by Doménech Quesada (2004) to the reality of this case study.

3. Results and discussion

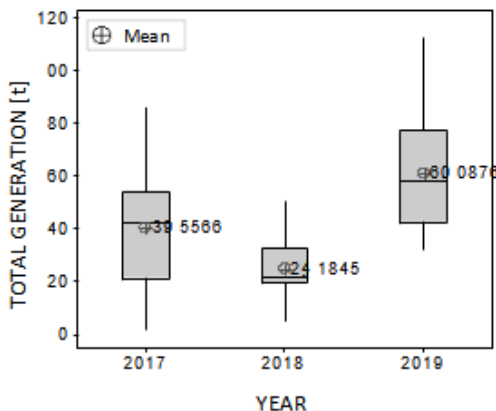
3.1. Solid waste generation

At "Mina do Andrade", 468 t of ISW were generated in 2017, 290.21 t in 2018, and 721.05 t

in 2019. Based on the statistical analyses of ISW amounts monthly generated, it was verified that the average monthly ISW generation underwent temporal variation with statistical significance for the period ($p= 0.001$), with 2019 differing from 2017 and 2018, which did not differ from each other, with the highest average being recorded in 2019 (Figure 1(A)). Considering the periods prior (phase 1) and simultaneous (phase 2) to the company expansion process, 721.46 t of ISW were generated in phase 1, and 764.48 t in phase 2, with statistically significant difference between the two phases ($p= 0.013$) (Figure 1 (B)).

This context suggests that the increase in ISW generation observed after the beginning of the company expansion in November 2018, and which extends to 2019, may be related to the construction stage of the new Itabirite concentration plant. After all, as pointed out by Christensen et al. (2019), this process usually leads to a significant increase in resource consumption and the amount of waste generated. Over the evaluation period, nine types of final destination were adopted for the ISW generated in the company, which, for evaluation purposes, were divided into two disposal categories: end-of-pipe treatments (including final disposal in landfills) and recycling (including reuse) (Table 2).

Annual assessment



(B) Prior and concurrent with the IP assessment

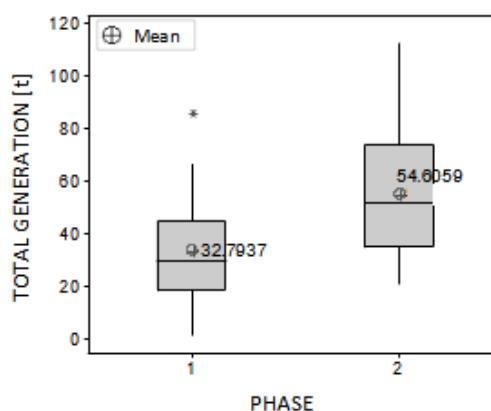


FIGURE 1 – Box-plot graphs indicating the monthly generation of industrial solid waste at “Mina do Andrade”: (A) annual assessment; and (B) evaluation of periods prior to and simultaneous to IP works.

SOURCE: the authors.

TABLE 2 – Types of final disposal of ISW at “Mina do Andrade” in 2017, 2018 and 2019.

Final destination categories	Final destination type	
End-of-pipe treatments	Co-processing/ incineration	
	Other treatments	Landfill
		Industrial landfill
		ETE
		Physicochemical treatment
Recycling	Internal recycling	Reuse in the production process
	External recycling	Recycling in association
		Reuse in external production processes
		Re-refining of used oil
		Sale

SOURCE: the authors.

In 2017, 91% of the amount of waste generated was sent to end-of-pipe treatments, while 9% of ISW was sent for recycling. In 2018, 46% of the waste generated was sent for recycling and 54% of the waste generated remained receiving end-of-pipe treatments. In 2019, the proportion of recycled waste decreased compared to the previous year, and only 24% was destined for such destination, which was due to the significant increase in hazardous waste compared to the previous year (about 400%). In this year, 73% of SW received end-of-pipe treatment. As for the period before and simultaneously with the IP, it was found that the treatment of waste using end-of-pipe techniques was mostly adopted in two phases, and, in the previous phase, co-processing/incineration was the most used treatment, while in the company expansion phase, the other end-of-pipe treatments predominated. This predominance of the adoption of end-of-pipe techniques for the final ISW destination is shown to be a negative aspect considering its incompatibility with the sustainable development of “Mina do Andrade”. This is because, although such methods have been improved over the last few years, they

act only to treat waste after it becomes evident as an environmental impact (Hilson, 2000).

3.2. Industrial Solid Waste (ISW) CCF

The total net CCF associated with ISW management was zero in the three-year period, as the gross CCF was smaller than the counter-footprint, which also generated a carbon debt for the company. This “carbon neutrality” in the ISW management was achieved through compensation for carbon sequestration by forested areas preserved within the limits of the company (cfco₂; Figure 2) and the reduction of emissions between the years 2017 and 2019 (gross CCF; Figure 2) (Casper, 2010).

The management of hazardous ISW generated most of the ISW emissions at “Mina do Andrade” in the three years evaluated. In 2017 and 2018, 99.99%, this waste accounted for 99.88% of emissions in 2017, 99.09% in 2018, and 79.29% in 2019. The largest gross hazardous waste CCF was generated by residual CSAO throughout the triennium (Table 3). Paper/cardboard and plastics were the non-hazardous SW most generating gross

CCF in the years 2017 and 2018, while rubber and tires were the largest CCF generators in 2019 (Table 3). This occurred because tires and rubbers, which

in 2017 and 2018 were sent to landfills, were now destined for co-processing, which led to increased emissions per ton of waste (Marañón et al., 2008).

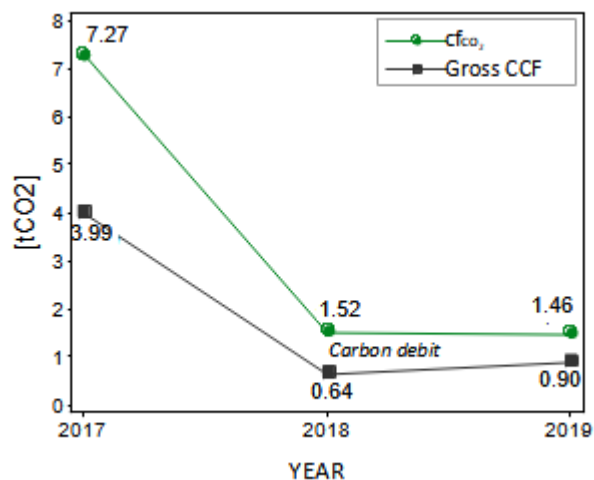


FIGURE 2 – Line graph indicating the evolution of cfco₂ and gross SW CCF at “Mina do Andrade” in the years 2017, 2018 and 2019. SOURCE: the authors.

TABLE 3 – ISW Corporate Carbon Footprint of “Mina do Andrade” in the 2017-2019 three-year period: gross CCF and net CCF.

Industrial Solid Waste		2017		2018		2019	
		CCF gross [tCO ₂]	CCF net [tCO ₂]	CCF gross [tCO ₂]	CCF net [tCO ₂]	CCF gross [tCO ₂]	CCF net [tCO ₂]
Non-hazardous	Non-recyclable waste	0.0006	-0.1226	0.0006	-0.1226	0.0007	-0.1509
	Paper/cardboard and plastic	0.0037	-0.0231	0.0048	-0.2031	0.0275	-0.5808
	Rubber and tire waste	0.0002	-0.0433	0.0003	-0.0633	0.1578	-0.1001
Hazardous	Material contaminated by oil/grease	0.0022	-0.0009	0.0325	-0.0134	0.1572	-0.0998
	Lubricating oil	0.0021	-0.0870	0.0000	-0.0004	0.0000	-0.0004
	CSAO residue	3.9830	-2.9563	0.6003	-0.4455	0.5497	0.5083
	Bathroom waste and septic tank	0.0004	-0.0506	0.0002	-0.0289	0.0009	-0.1213
	Least generated dangerous ISW	0.0000	0.0000	0.0008	-0.0030	0.0028	-0.0139
TOTAL		3.9923	-3.2838	0.6396	-0.8803	0.8966	-0.5589

SOURCE: the authors.

Between the final and initial years of this study, the demand for carbon-sequestering bioproductive areas for managing ISW generated in the company decreased by approximately 78%; and, when comparing the previous phases and phases simultaneous to IP works, there was an 80% drop in consumption. In 2017, the highest gross ISW CCF of the three-year period evaluated was recorded, while 2018 recorded the lowest value (Figure 3 (A)), and there was a temporal variation with statistical significance for carbon emissions between the years under evaluation ($p=0.000$; Figure 3 (A)), in which 2017 and 2018, values differed from each other and 2019 did not differ from the other years. Analyzing the periods before (phase 1) and simultaneous to the company expansion process (phase 2), it was verified that the gross ISW CCF was not significantly different between the two phases ($p=0.638$; Figure 3 (B)).

In 2017, for the management of each kilogram of ISW generated in the company, approxima-

tely 8.45×10^{-5} tons of CO_2 were emitted, in 2018 around 1.55×10^{-5} tCO_2 were emitted per kilogram of generated ISW, while, in 2019, the lowest CO_2 emissions per kilogram of ISW were recorded, totaling 1.47×10^{-5} tCO_2 emitted.

This decrease in environmental impact, when associated with increased ISW generation (Figure 1), may be associated with the permanence of corrective actions to impacts generated by waste in favor of preventive strategies for cleaner production (CP) (Giannetti & Almeida, 2006). After all, based on the restructuring of the environmental policy for SW management at “Mina do Andrade”, part of actions implemented in the project were in compliance with CP principles (non-generation, minimization or recycling), while most of the generated waste remains treated by end-of-pipe corrective measures (Table 2).

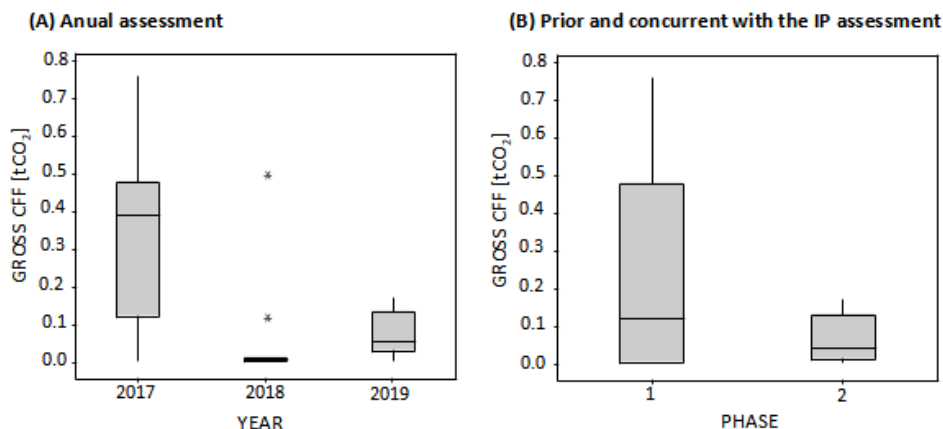


FIGURE 3 – Box-plot graphs indicating the gross hazardous ISW CCF at “Mina do Andrade”: (A) annual assessment; and, (B) evaluation of periods prior to and simultaneous to IP works.

SOURCE: the authors.

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As observed at “Mina do Andrade”, most of the SW generated by the metallic minerals mining sector in MG, evaluated in recent years by FEAM, was destined to end-of-pipe treatments (FEAM, 2018a, 2017, 2016b, 2015, 2014). This situation is a great challenge for the promotion of sustainable development in the sector, because, as pointed out by Marañón et al. (2008), this type of SW disposal generates large CO₂ emissions and is not compatible with the sustainable development of the sector (Hilson, 2000).

The reduction of gross CCF from the implementation of new waste management policies in January 2018 corroborates the assertions brought by Hodgkinson & Smith (2018), which suggest that the adoption of CP technologies to minimize the generation of waste, reuse it and recycle it are also strategies for mitigating climate change via decarbonization of ore production chains. The non-generation of ISW exempts the company from emissions derived from the management of the pollutant, not accumulating ISW CCF in the final product. The same occurs with the reuse of by-products in the

production process itself, which is a destination that allows a beneficial application of waste (Lottermoser, 2011). Internal reuse exempts the company from emissions generated by waste management, which must be accounted for in the company's material footprint. These advantages were clearly observed in this study, from the reuse of wood residues within the company itself. The reuse of by-products in external production processes also contributes to reduce the ISW CCF of “Mina do Andrade”. The donation and/or sale of the by-product to another company transfers the responsibility for the disposal of such material to the buyer/receiver. Thus, when incorporating the product into its production process, the footprint associated with it is computed in the material footprint of the receiver, exempting the generator from such an impact. For example, when auctioning used batteries and donating organic waste, the responsibility for the final destination of this waste becomes the responsibility of the buyer or receiver, as well as the footprint associated with the SW management, which will be considered inputs of the new system (outsourcing).

Unlike these CP strategies, the external recycling of paper, cardboard and plastics accumulated for the company the carbon production associated with the process of extracting reusable components or transforming these residues into products (Figure 4 (A)). In 2017, waste recycling accounted for about 0.10% of CO₂ emissions for ISW management, while for 2017 and 2018, these values were approximately 0.75% and 3.10%, that is, most of emissions originated from end-of-pipe treatments (99.90% in 2017, 99.25% in 2018 and 96.90% in 2019) (Figure 4).

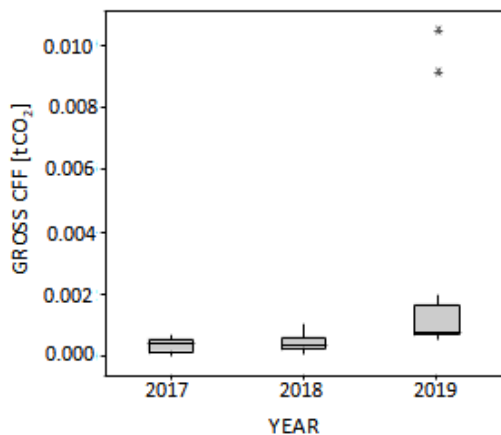
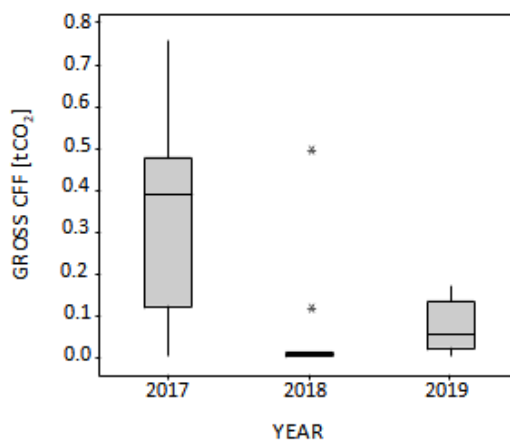
(A) External recycling**(B) End-of-pipe treatments**

FIGURE 4 – Box-plot graphs indicating the gross ISW CCF at “Mina do Andrade” in the three-year period evaluated. (A) waste recycled outside the company; and, (B) end-of-pipe treatments.

SOURCE: the authors.

The main ISW destined for end-of-pipe treatments include non-recyclable waste (Figure 5 (A)), sent to landfill, tire and rubber waste (Figure 5 (B)), sent to industrial landfill in 2017 and 2018 and co-processed in 2019, material contaminated by oil/grease (Figure 5 (C)), sent to industrial landfill in 2017 and in 2018 and co-processed in 2019, used lubricating oils (Figure 5 (D)), which were recovered, Water and Oil Separator Box (CSAO) (Figure 5 (E)), co-processed in 2017 and 2018 and destined for physicochemical treatment in 2019, bathroom waste and septic tank (Figure 5 (F)), sent to the Sewage Treatment Station (ETE). Together, these ISW correspond to more than 99.99% of emissions generated by waste destined for end-of-pipe treatments in the company in the three-year period. Other waste includes burnt out light bulbs, metallic scrap contaminated by hazardous waste and health service waste, which generated less than 0.01% of emissions in the three-year period.

The adoption of CP strategies proved to be effective in reducing and even neutralizing carbon emissions generated by the ISW management at “Mina do Andrade”. Doménech Quesada (2006) also suggests the acquisition of bioproductive areas as a means of increasing CF, thus minimizing the company's carbon footprint, contributing to the mitigation of climate change. Such a carbon sink may also allow companies to participate in the carbon market and improve their corporate social responsibility (Doménech Quesada, 2006). Doménech Quesada (2006) explains that the adoption of CCF on a large scale would allow the private sector to contribute to the conservation of ecosystems, while improving its environmental performance. The strategy proposed by Doménech Quesada (2006) is considered especially important in the context of “Mina do Andrade”, considering that the company is inserted in a large continuous extension of preserved Atlantic Forest.

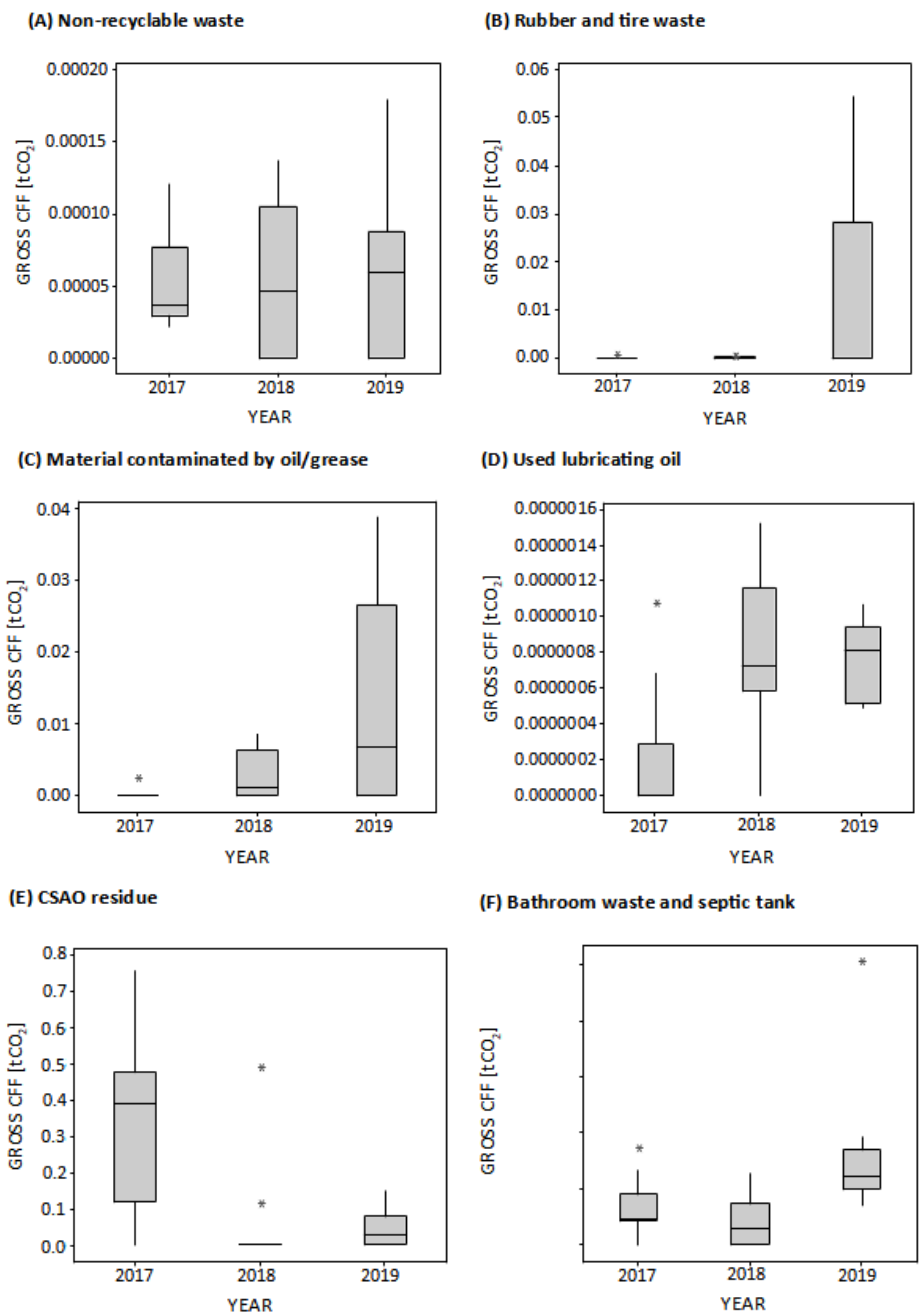


FIGURA 5 – Box-plot graphs indicating the gross ISW CCF destined to end-of-pipe treatments at “Mina do Andrade” in the three-year period: (A-F) Solid Waste treated by end-of-pipe techniques.

SOURCE: the authors.

3.3. Mining Waste (MW) CCF

Unlike the net ISW CCF generated in the company, the total mining waste CCF was 342.51 tCO₂ per year. So, the disposal of waste rock in piles generated most (approximately 99%) of the company's gross SW CCF in the evaluation period. It is important to emphasize that the use of land by mining tends to be greater in open pit mining in mountainous areas, as in the case of “Mina do Andrade”, configuring a challenge for the sustainable development of the company and the sector, since changes in land use for this activity are inevitable (Murakami et al., 2020). Therefore, the adoption of strategies to reduce the CCF generated by the land use generated by waste piles in companies with these characteristics, such as “Mina do Andrade” aiming at reducing the ecological impacts generated by the sector. Lottermoser (2011) proposes the re-processing of mining waste as a possible sustainable solution for MW management, so that the itabirite concentration in the company, from 2020, proves to be a sustainable solution to mitigate the impacts of this waste. However, as pointed out by Gan & Griffin (2018), the processing of iron ores with lower content can lead to higher GHG emissions when compared to purer ores, so that the company must concentrate efforts on reducing the increase in CO₂ emissions throughout the itabirite concentration process. Lottermoser (2011) also points out other options for MW rehabilitation, which include: filling of the pit; inclusion in dams, roads, pavements, foundations and civil construction; burial of waste in landfills; substrate for revegetation of degraded

areas; asphalt component, cement and barren waste rock produced at “Mina de Andrade”, depending on the waste mineralogical, geochemical and geotechnical characteristics (Lottermoser, 2011).

4. Concluding remarks

This work filled part of the existing gap on carbon emissions for Solid Waste (SW) management in mining projects, considering the low number of peer-reviewed studies on the mining Carbon Footprint. So, in a pioneering way, the Corporate Carbon Footprint (CCF) generated by the management of Industrial Solid Waste (ISW) and Mining Waste (MW) of an iron ore mining company was estimated, evaluated and discussed. CCF associated with ISW was estimated as null throughout the evaluation period. This is because, although the total CO₂ generation was positive, the large extension of forested areas belonging to the project is able to meet this demand and even generate carbon credits for the project. However, the same did not occur for MW, which generated a carbon deficit for the company in the evaluation period. The results of this work highlighted that the adoption of end-of-pipe technologies and the suppression of vegetation for the disposal of waste rock are critical aspects of the SW management CCF at “Mina do Andrade”, providing an analytical basis for future low-carbon actions and policies. Thus, this work contributes to highlight the metrics that allow better management and control of impacts generated by mining and therefore contribute to the pursuit of sustainable development in the mining sector.

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