If we had a Consistent System for Using Pyrite in Coal Mining in the State of Santa Catarina, Brazil, What Would the Scenario Be?

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Abstract

In Santa Catarina State, Brazil, almost 400 million tons of coal waste rich in pyrite have already been deposited on the surface, causing severe environmental damage due to acid mine drainage (AMD) generation. In the 1980s, coal waste was reprocessed to concentrate pyrite for the production of sulfuric acid; however, the practice was discontinued. This study assessed the benefits that would have occurred if pyrite recovery had continued. The results showed that pyrite recovery would reduce waste mass by 14.1%, decrease the total sulfur content in the waste from 6.9% to 2.2% and lower acid generation and lime consumption in AMD treatment. This would help simplify the decommissioning and recovery of degraded areas, and improve sulfuric acid supply in Brazil.

Keywords: Acid mine drainage, pyrite recovery, coal waste, degraded areas

Introduction

Coal mining in Brazil only occurs in three states in the southern region (Fig. 1). The state of Santa Catarina is facing the greatest environmental challenges. Coal mining began in the late 19th century and, for decades, occurred without environmental care. The coal in the region has a high sulfur content, and the mechanised underground mining process promotes the transport of a large volume of rock waste to the surface. To meet the standards of the local thermoelectric plant, the coal needs to be processed to remove pyrite and associated rocks, generating 50–70% waste. It is estimated that almost 400 million tons of coal waste have already been deposited on the surface of the Santa Catarina Coalfield (Weiler and Schneider, 2019). The result is a legacy of immense waste deposits with a high pyrite concentration (10-12%), presenting a major environmental problem. Acid mine drainage (AMD) has contaminated the soil, groundwater, and surface water.

Currently, the recovery of environmental liability has been addressed through public civil action with local mining companies. These actions are gradually mitigating the effects of AMD on the soil, groundwater and rivers of the region. However, many areas remain 'orphan sites' and continue to impact the environment (Rocha-Nicoleite *et al.*, 2017). Although legislation and actions to mitigate environmental damage have advanced since the 1990s, some areas remain affected. Models indicate that AMD may continue to be generated for over 500 years, requiring effluent treatment and long-term monitoring of these areas. Fig. 2(a) represents an area of irregular waste disposal directly on the soil, and Fig. 2(b) shows a river contaminated by AMD in the coal mining region of Santa Catarina.

Geologically associated with carbonaceous matter, there are pyrite nodules. The production of elemental sulfur, sulfuric acid, and other products from pyrite can provide the country with essential raw materials for industry without the need for imports. In

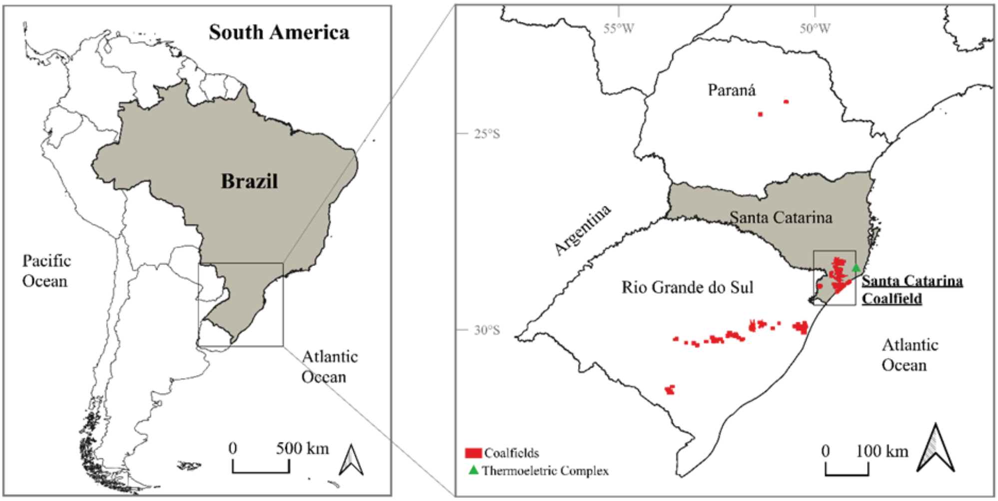

Figure 1 Location of the study region, in Santa Catarina Coalfield, which supplies the Jorge Lacerda Thermoelectric Complex.

1968, semi-industrial scale studies conducted by the fertiliser company, later transformed into 'Indústria Carboquímica Catarinense' (ICC), demonstrated that 70–80% of sulfur could be recovered from pyrite concentrates. The importance of sulfuric acid production for fertiliser manufacturing was highlighted. It is estimated that during its operational period, ICC consumed around 2.3 million tons of pyrite, supplying 15% of Brazil's sulfuric acid demand between 1985 and 1988 (Souza, 2007; Goularti and Moraes, 2009).

However, ICC closed in 1992, declaring bankruptcy and abandoning the pyrite concentration plant near the coal production site and the sulfuric acid plant near the Imbituba port, SC (Souza, 2007). Some mining companies attempted to include pyrite concentration in their beneficiation plants, but the small volume produced and the lack of a consumer market restricted this initiative. Thus, the practice was discontinued and is considered one of the major setbacks in the sector because it shifted from a clear circular economy to a linear economy (coal to thermoelectric power).

Based on the problem presented, this study assessed the benefits that the use of pyrite could have brought to the southern region of Santa Catarina if pyrite concentration had continued. This would have prevented the disposal of a substantial amount of pyrite with the waste on the surface, reducing AMD and all related impacts while also providing a raw material source for sulfuric acid production.

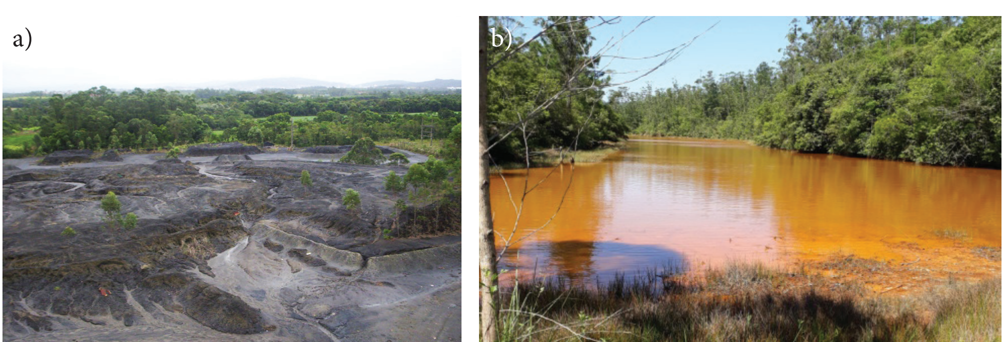

Figure 2 Irregular coal waste disposal on the surface (a) and a river contaminated by acid mine drainage (AMD) in the coal mining region of Santa Catarina (b).

Methods

Quantitative data on coal production and waste generation in Santa Catarina from 1925 to 2022 was provided by 'Sindicato Indústria de Extração Carvão Estado de Santa Catarina' (SIECESC) (2025). The quantity produced in the period from 2023 to 2025, not yet disclosed, was estimated based on the trend of recent years.

The mass balance of the pyrite fraction was obtained from the work of Weiler and Schneider (2019), who separately evaluated the two main coal layers explored: the 'Barro Branco Seam' and the 'Bonito Seam'. The values do not differ much in terms of sulfur content and mass recovery, and an average value was adopted. Only the gravimetric processing of the coarse fraction (50.8 + 2.0 mm) was considered, which was used by ICC in the concentration of pyrite.

Briefly, representative samples from both seams were gravimetrically processed in a dense medium of iron–silicon (Fe-Si) to obtain two density fractions: below 2.7 g cm^{-3} (waste rock with low pyrite content) and above 2.7 g cm^{-3} (pyrite concentrate). The processing products were characterised in terms of sulfur content (pyritic, organic, sulfate, and total) and acid generation potential. The total sulfur analysis was conducted using a Leco SC 457. Sulfur forms (pyritic and sulfate) were analysed using titration procedures according to ASTM D2492–02 (ASTM, 2012). Organic sulfur was calculated from the difference between total sulfur and pyritic and sulfatic sulfur. The account provided that approximately 82% of S is in the form of pyrite, 15% in the form of organic S, and 3% as sulfate. The acid generation potential was determined using the classical acid–base accounting method described by Sobek *et al.* (1978).

Results and Discussion

Fig. 3 presents historical data regarding waste production in the Santa Catarina coal region. An increase in waste production can be observed in the 1970s and 1980s, resulting from the Brazilian Government's encouragement of coal production due to the 1973 Oil Crisis. In the following decade, due to incentives for the sector, a coal waste processing plant was also implemented to concentrate pyrite, intended for the production of sulfuric acid for fertilisers. Since the 1990s, the production of coal waste in the region has averaged 4.1 million tons per year (SIECESC, 2025).

Table 1 presents the result of the densimetric separation of the waste, considering the pyrite fraction above 2.7 g cm^{-3}. The mass fraction density above 2.7 g cm^{-3} (pyritic concentrate d ≥ 2.7) accounted for 14.1% by mass, with a total sulfur content of 35.4% (54% pyrite). The remaining fraction (waste fraction d < 2.7) makes up 85.9% of

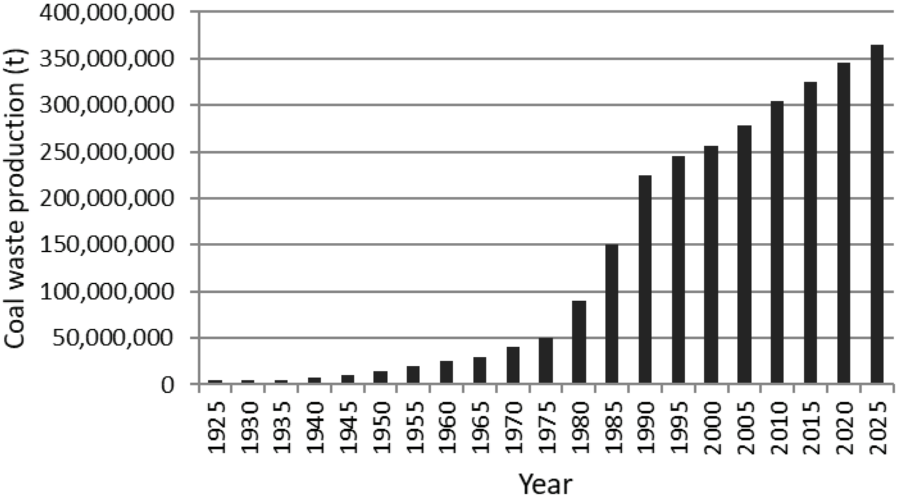

Figure 3 *Accumulated coal waste produced in the carbonific site of Santa Catarina, Brazil.*

Table 1 *Results in terms of mass and sulfur content of the raw waste and after its densimetric division at a density of 2.7 g cm⁻³.*

	Raw waste	Waste Fraction (d < 2.7 g cm^{-3})	Pyrite Concentrate (d ≥ 2.7 g cm^{-3})
Mass (%)	100.0	85.9	14.1
Stotal (%)	6.9	2.2	35.4
Spyrite (%)	5.7	1.6	31.1
Ssulfate (%)	0.2	0.1	0.5
Sorganic (%)	1.0	0.5	3.8

the mass, with only 2.2% of total sulfur (3.3% pyrite). Basically, with a gravimetric process of coarse particles of coal waste, there is a potential to remove 77% of the pyrite present in the waste.

Fig. 4 compares the historical accumulation of the discarded mass of coal waste and the amount of coal waste if the waste was processed to concentrate pyrite. The historical reduction in the period from 1925 to 2025 would not exceed 6%.

Fig. 5 compares the historical accumulation of total sulfur in the discarded mass of coal waste and the amount of total sulfur if the waste was processed to concentrate pyrite. In this scenario, the historical reduction in total sulfur discharged in coal dumps in the period from 1925 to 2025 decreases to 27%.

The data presented here related to the concentration of pyrite do not solve the problem of the volume of waste deposited. However, they make it possible to restrain the amount of pyritic sulfur deposited in the environment. Previous geochemical tests by Amaral Filho *et al.* (2017) showed that the coal desulfurisation process in Santa Catarina does not prevent AMD generation; however, it substantially decreases the rate and net amount of metals, salts, and acidity. Additionally, it was estimated by Weiler *et al.* (2016) that a cut in the costs of reagents (basically lime) of approximately 85% is expected in acid mine treatment plants if coal desulfurisation procedures were adopted.

Currently, with the disruption of the pyrite production chain, actions are mainly focused on the safe land disposal of waste

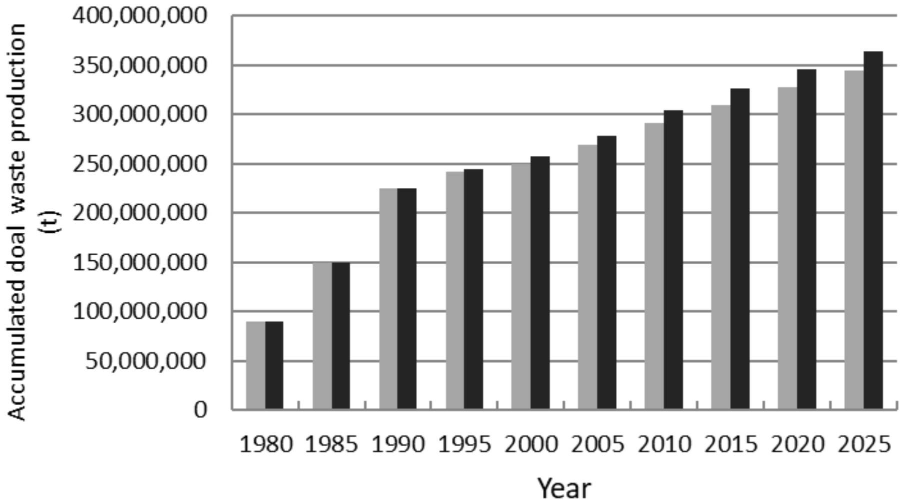

Figure 4 *Accumulated coal waste produced from 1980 to 2025 (right, black) and simulated coal waste production in the same period considering the use of the pyritic fraction (left, grey).*

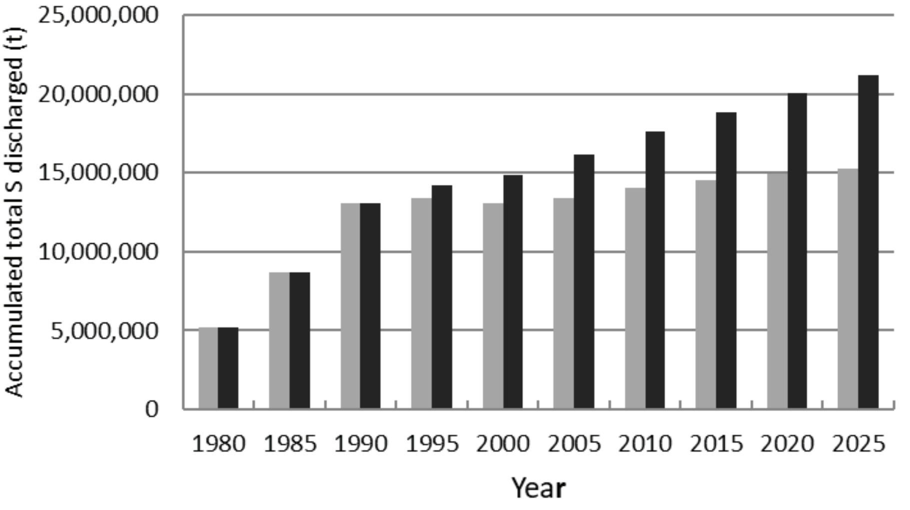

Figure 5 Accumulated total sulfur discharged from 1980 to 2025 (right, black) and simulated total sulfur discharged in the same period considering the use of the pyritic fraction (left, grey).

in modules, with a small fraction of pyrite concentrates being sold to sulfuric acid production units in central Brazil and some backfill initiatives (returning waste to open chambers in the mining process) (Amaral Filho *et al.*, 2013). However, the sector's active community agrees that utilising pyrite is part of the necessary set of actions for the environmental recovery of the coal mining region in Santa Catarina (de Oliveira *et al.*, 2019; Weiler *et al.*, 2019; Ferreira *et al.*, 2021).

In addition, the region has the potential to supply 400,000 to 800,000 metric tons of pyrite concentrate (50–60% pyrite) per year. If converted into sulfuric acid, this would represent an increase of at least 500,000 tons of the acid annually to Brazil's production (Weiler and Schneider, 2019). This amount could help meet this Brazilian deficit in this input. It is important to remember that Brazil plays a key role in global food supply and that 80% of the sulfuric acid required in the country is used for fertiliser production.

Conclusions

The decommissioning of the coal mining sector in Brazil is in progress. The pollution scenario might not have been resolved by pyrite concentration and utilisation, but the level of the damage would have been lower, and finding solutions would have been easier. If the region had been seen both as a coal and a sulfide deposit, environmental management would have been facilitated, and less of a pollution legacy would have been left for future generations. Therefore, it is suggested that new coal mining projects in the region consider waste processing for pyrite concentration and that existing operations be restructured accordingly. Additionally, another opportunity would be to reprocess surface-disposed wastes, treating this material as ore rather than waste. Naturally, this should be based on technical, economic, environmental and legal feasibility, highlighting the importance of future studies focused on these aspects.

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