



An overview of the coal circularity in Brazil: A new sustainable approach based on sampling method, characterization, and waste valorization

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ABSTRACT

Coal is a key energy source globally, and Brazil holds substantial reserves. However, approximately 50% of the coal extracted in Brazil is discarded as waste, often mixed into a single material without selective characterization. This study aims to establish a framework to help mining companies identify and implement strategies for sustainable coal mining practices in the study region. Residual fraction samples were collected and analyzed for their characteristics and potential applications. The results showed that the clay content in the waste is influenced by the age and depth of the coal deposits, while the beneficiation process determines the pyritic content. Based on these findings, four groups of residual fractions were identified for specific applications. Group 1, with higher carbon content, is suitable for processing and carbon concentration. Group 2, characterized by low pyrite content, coarse granulometry, and neutral pH, may be used to concentrate clay minerals for ceramics and mortars. Group 3, rich in clay minerals, is suitable for fertilizers, techno-soils, pozzolans, and geopolymers. Group 4 includes samples with potential for pyrite concentration. This study highlights the value of systematic waste sampling and evaluation, providing an effective strategy to promote the circular economy. This approach supports sustainable development in the research region and beyond by unlocking the potential of coal mining waste.

1. Introduction

Since the Industrial Revolution, coal has been one of the most widely used fossil energy sources to power the world economy, being found in over 70 countries on different continents (Shafiee and Topal, 2009). Since then, governments have realized that using coal was the key to industrialization, and consequently, coal mines have been extensively developed (Taha et al., 2017). Although coal consumption significantly declined during the COVID-19 pandemic 2020, global demand has doubled in the last three decades, reaching 8.68 billion tons in 2023.

Global production reached 8.99 billion tons in the same year. The electrification of transport, increased use of air conditioning, and the increase in sectors using electricity are driving the increase in consumption since electricity accounts for 2/3 of the world's coal consumption (IEA, 2024).

Despite the decrease in the use of coal for electricity generation in several parts of the world, this activity is still a reality in Brazil. The study region has several landfills with coal mining wastes generated in the past that can be used for various applications. Recently, a law that extends the operation of coal-fired thermal plants until 2040 was

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sanctioned in Brazil, reflecting on the continuity of the generation of this waste (BRASIL, 2022). This information confirms the need for further research to value the sector's waste and make it more environmentally, socially, and economically sustainable.

Coal reserves are extensively available worldwide, with over one trillion tons of known resources, enough to sustain current use for 190 years (British Petroleum, 2021; IEA, 2021). Brazil is ranked 15th globally by British Petroleum (British Petroleum, 2017; CGEE, 2012). In production, it ranks 26th, with an annual volume of around 5 million tons (SIECESC, 2020).

Coal is used in two ways in Brazil: as a fuel for power generation (national coal), which includes industrial energy use, and in the steel sector for the manufacturing of coke, pig iron, and steel (Amaral, 2014). Brazil is not among the world's largest producers since its domestic coal lacks qualities suited for steelmaking due to a high percentage of ash. As a result, coal must be imported, primarily from Australia, the United States, Russia, Canada, Colombia, Venezuela, Indonesia, and South Africa (MEM. de minas e energia, 2010). Although Brazil is not one of the world's largest producers in this sector, its production percentages are significant. These must be discussed and explored to achieve economic, social, and environmental sustainability.

In 2021, coal production in Brazil was estimated to reach over 6 million tons, with Santa Catarina accounting for 2.4 million tons (SIECESC, 2022). In the instance of Santa Catarina, around 65% of the ROM (Run-of-Mine) coal is dumped as waste with no commercial value following mineral processing. This high percentage of waste is attributable to the coal layers' thin thickness and intercalation with sedimentary rocks (shales, siltstones, and sandstones), pyrite nodules (iron disulfide - FeS_2), and ash, as well as mining automation (Weiler et al., 2014). Coal extraction and processing incur significant expenses for mining corporations and have additional impacts on the environment. This issue significantly impacts the southern region of Santa Catarina due to the coal peculiarities. According to a CPRM report, Geological Survey of Brazil (Suffert et al., 1977) since 1977, it has been adopted as a criterion that when the coal layer is less than one-third the thickness of the non-carbonaceous layer, this coal bed is considered non-minable.

Such wastes are usually mixed and treated as a single material without addressing and correlating their specific characteristics and potential application in new processes and products. Reusing coal waste after beneficiation (specific residual fractions) and avoiding continuous generation are significant challenges that must be addressed systematically and holistically to promote sustainable development and the circular economy. Most studies focus on a specific beneficiation technology, a specific coal mine, or wastes collected from industrial landfills/deposits. Rare studies examine a large coal mining camp for solid waste reduction and valorization in this way.

Innovative management and recycling concepts for coal mining waste are being developed in Europe and worldwide. One potential solution is to use coal waste as a raw material for sustainable construction products, promoting the circular economy in coal mining areas (Vo et al., 2022). Other research suggests that this waste could be used to make aggregates for construction (Kinuthia et al., 2009; Nixon and Gartner, 1980; Santos et al., 2013), hot mix asphalt (Modarres and Rahmzadeh, 2014), building ceramics materials (Lemeshev et al., 2004). Lemeshev et al. (2004) demonstrated that coal mining waste is viable for producing construction ceramics. The waste content can be as high as 50% while still complying with local regulations (Lemeshev et al., 2004). Modarres and Rahmzadeh (2014) investigated the effects of coal waste powder as a filler material in hot mix asphalt. Their results indicated that, compared to the reference mix, which contained limestone powder, the use of coal waste and its ash led to greater stability and an increased resilient modulus (Modarres and Rahmzadeh, 2014).

Recently, CMW has been used in various agricultural applications, including as a mixed cropping substrate, slow-release fertilizer, and soil water retention agent. This has led to the widespread recognition of

CMW as a valuable resource in agriculture. Research on its utilization in agricultural production holds considerable ecological and economic importance. It meets the high agricultural demands of major producing nations and facilitates the large-scale management of CMW (Zheng et al., 2024).

CMW contains various minerals and elements, including aluminum, silicon, iron, and rare elements, such as gallium, lithium, titanium, and germanium. It also contains minerals like kaolin and coal. A critical focus of secondary recycling of CMW is metal recovery (Shao et al., 2022; Zheng et al., 2024). For instance, Cao et al. (2024) studied the recovery of lithium from coal mining waste. The technology for recovering these materials primarily involves pretreatment, lithium leaching, and selective removal from the leaching solution. Although the extraction process is still in the laboratory stage, it follows a similar enrichment and leaching approach as that used for lithium ore and has good perspectives for the future (Cao et al., 2024). Finally, CMW has applications in power generation and environmental restoration (Zheng et al., 2024). CMW may be utilized in gas purification, electrochemistry, and solar energy conversion and storage (Guo et al., 2024).

In Brazil, over the years, CMW has been classified as R1 (pyritic), R2 (clayey), and R3 (carbonaceous). This nomenclature comes from the processing technology, consisting of 3-cut hydraulic jigs, producing CMW with different densities. Currently, each company has its own processing method with varying sequences for coal concentration. As a result, various fractions of waste are generated at each stage, with specific characteristics related to the geological aspects of the mineral's origin and the beneficiation process applied. The waste is disposed of as a single waste and sent to landfills. In the region studied, some mining companies currently use, for example, the dense medium cyclone as one of their coal concentration equipment, which uses magnetite in the process. The waste discarded from this processing does not fit into the R1, R2, or R3 nomenclatures.

NMC (Natural Medium Density) technology has been used in the United Kingdom for several years. This system uses fine clay and shale particles to separate the particles. The result is waste generated with characteristics typical of this type of processing (Chu et al., 2017). In China, based on the concentration of compounds in the extracted coal seam, gangue, as the tailings are called in China, can be divided into carbonaceous clay, sandstone, siltstone, limestone, or high-alumina gangue. Therefore, the various types of waste generated have different characteristics (Cao et al., 2024).

In this work, the selective flow of waste materials obtained after coal beneficiation from six mining companies in southern Santa Catarina, Brazil, which supply coal to thermal power plants in the region, was evaluated for the first time. The study's innovation is also in the sampling selection of the materials to be studied, which updates the terminology used for decades in studies of coal wastes in the study region, such as R1 (pyritic), R2 (clayey), and R3 (clayey, and carbonaceous). The study treats waste as secondary resources, examining specific geolocations, geological layers, and processing stages to identify potential by-product applications. While some studies have explored this approach with other materials, this research is essential and innovative in the context of coal mining waste in Brazil. By adopting this approach, mining companies can identify the pathways required to achieve sustainability in coal mining within the study region.

2. Experimental

2.1. Materials

The materials used in this study were generated by regional mining companies that are part of the group of suppliers of the Jorge Lacerda Thermoelectric Complex's energy quota, located in Capivari de Baixo—SC, Brazil. Six mining companies (Fig. 1) were identified in the Santa Catarina coal basin, which is approximately 2000 km² and lies between the Serra Geral formation and the coastal region.

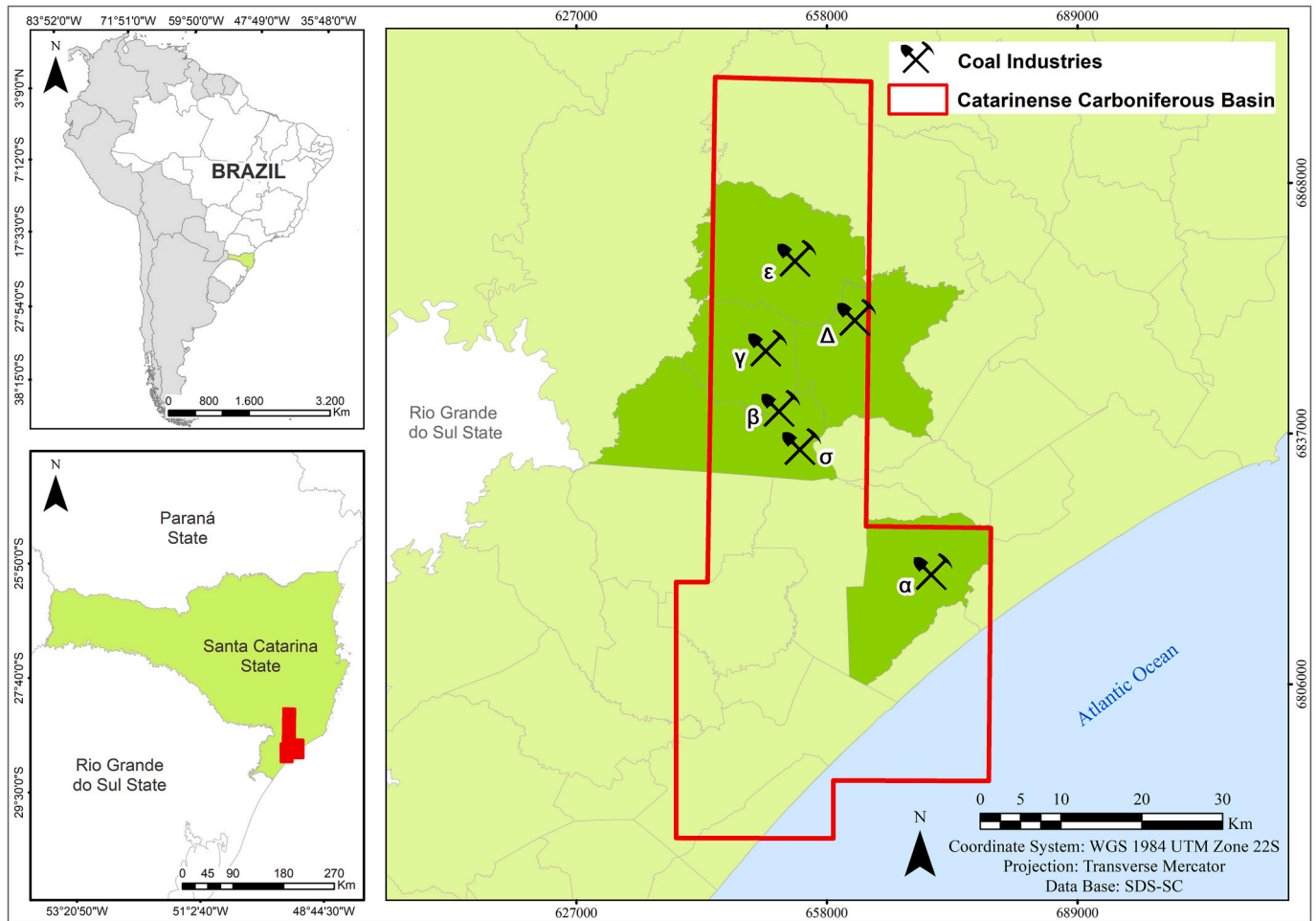


Fig. 1. Santa Catarina coal basin and location of the mining companies studied.

Through reflection and literature review, it was attempted to establish selective flows for using residual fractions contained in the various materials generated by the mining of energetic coal in the Santa Catarina Carboniferous Basin. In the study region, a sampling method was used to collect waste as it was generated (in fractions) to account for company differences, geolocational characteristics, and beneficiation processes (technological characteristics).

Twenty-four residual fractions were collected and coded. The codes follow the following order: layers, processing, company, and an indication of the disposal order (numerically). The acronyms BB for the Barro Branco (white clay) layer, BO for the Bonito (pretty) layer, and RE for “reject deposits” were used to identify the layers. The processing steps are indicated as jig (Ji), dense medium (Md), air table (Ma), crusher (Br), cyclone (Ci), flotation (Fl), and settling basin (Bd). In the sequence, the company is presented by Greek letters α , β , γ , Δ , ϵ and σ . This coding is presented in Table 1, with each mining company being assigned a specific color as follows: Company α : shades of yellow; Company β : shades of grey; Company γ : shades of red; Company Δ : shades of magenta; Company ϵ : shades of green; and Company σ : blue.

Visits were made to companies to understand better the manufacturing process and the characteristics of the mining sector. In this work, the production processes were described in detail to correlate the processing with the features of each collected waste fraction.

The mining company α (alpha), located in the middle third of the Santa Catarina coal basin, extracts coal from the white clay layer (BB). For coal concentration, it has a beneficiation plant (dense medium, cyclone, and flotation) that produces three residual fractions: BB:Md(α), BB:Bi(α), and BB:Fl(α). Following ROM extraction, the ore undergoes

crushing and sieve separation. The coarse fraction is submitted for gravimetric coal separation by dense medium (using magnetite), resulting in the company’s initial residual fraction, BB:Md(α). On the other hand, the fine fraction is beneficiated using the cyclone process, yielding the residual fraction BB:Bi(α). The mining business classifies the crushing fraction as ultrafine, which is then treated by flotation and press filter to produce the residual fraction BB:Fl(α), see Fig. 2.

The mining company β (beta) works with regrinding old coal waste deposits where the concentration of coal is carried out by jigging. According to the company β , it is possible to concentrate 10% of energy coal, and the remaining 90% becomes waste and is sent to controlled landfills. Coal concentration is carried out in jigging, generating six residual fractions identified by RE:Bd(β), RE:Ji(β)-1, RE:Ji(β)-2, RE:Ji(β)-3, RE:Ji(β)-4, RE:Ji(β)-5. It is observed that in the concentration of old deposits, the use of two beneficiation routes occurs, a route with jig of two cuts where in the first cut the residual fraction RE:Ji(β)-1 is generated and in the second cut the residual fraction RE:Ji(β)-2. For the route with the three-cut jig, the residual fractions RE:Ji(β)-3, RE:Bd(β)-4, and RE:Ji(β)-5 are generated in the 1st, 2nd and 3rd pass, respectively (Fig. 2). The washing water used in the processing and the fine powders from the process are sent to the settling basin, generating the residual fraction RE:Bd(β).

At the mining company γ (gamma) residual fractions BO:Md(γ), BO:Ji(γ)-1, BO:Ji(γ)-2, and BO:Ji(γ)-3 were collected. The mining company γ has two beneficiation plants, as shown in Fig. 2. In the primary beneficiation, three residual fractions are generated: BO:Ji(γ)-1, BO:Ji(γ)-2, and BO:Md(γ). The residual fractions BO:Ji(γ)-1 and BO:Ji(γ)-2 were collected, respectively, in the first and second discard of the jig.

Table 1

Residual fractions collected from layer, beneficiation process, and mining company.

Extracted Coal Layer	Beneficiation Process	Mining Company	Code
Barro Branco	Dense Medium	α ●	BB:Md(α)
Bonito	Dense Medium	γ ●	BO:Md(γ)
Bonito	Dense Medium	ε ●	BO:Md(ε)
Bonito	Jig	γ ●	BO:Ji(γ) - 1
Bonito	Jig	γ ●	BO:Ji(γ) - 2
Bonito	Jig	γ ●	BO:Ji(γ) - 3
Rejeito (reject deposits)	Jig	β ●	RE:Ji(β) - 1
Rejeito (reject deposits)	Jig	β ●	RE:Ji(β) - 2
Rejeito (reject deposits)	Jig	β ●	RE:Ji(β) - 3
Rejeito (reject deposits)	Jig	β ●	RE:Ji(β) - 4
Rejeito (reject deposits)	Jig	β ●	RE:Ji(β) - 5
Bonito	Jig	ε ●	BO:Ji(ε)
Barro Branco	Jig	ε ●	BB:Ji(ε) - 1
Barro Branco	Jig	ε ●	BB:Ji(ε) - 2
Rejeito (reject deposits)	Jig	σ ●	RE:Ji(σ)
Rejeito (reject deposits)	Settling Basin	β ●	RE:Bd(β)
Barro Branco	Air Table	Δ ●	BB:Ma(Δ) - 1
Barro Branco	Air Table	Δ ●	BB:Ma(Δ) - 2
Barro Branco	Air Table	Δ ●	BB:Ma(Δ) - 3
Barro Branco	Flotation	α ●	BB:Fl(α)
Barro Branco	Crusher	Δ ●	BB:Br(Δ)
Barro Branco	Cyclone	Δ ●	BB:Ci(Δ) - 1
Barro Branco	Settling Basin	Δ ●	BB:Bd(Δ)
Barro Branco	Cyclone	α ●	BB:Ci(α)

Whereas the residual fraction BO:Md(γ) was collected after the dense medium beneficiation of the main scrubber. The secondary beneficiation feed is composed of the residual fractions BO:Ji(γ)-1, BO:Ji(γ)-2, and BO:Md(γ) submitted to jigging, resulting in a single residual fraction, identified as BO:Ji(γ)-3.

The Δ (delta) mining company is the only one with open pit mining (Barro Branco layer, BB) and dry processing (Fig. 2). The BB layer presents reasonable uniformity and is subdivided into Forro, Quadração, and Banco. In the dry processing by air table, three residual fractions were collected and identified as BB:Ma(Δ)-1 (from Forro sub-layer), BB:Ma(Δ)-3 (from Banco sub-layer), BB:Ma(Δ)-2 (from Quadração sub-layer). BB:Br(Δ) (originating from the fines of the Quadração sub-layer) mainly comprises clays discarded in the crushing process before the air table separation. The fines fraction resulting from the air table is destined for a wet coal concentration plant. Two residual fractions identified as BB:Ci(Δ)-1 and BB:Bd(Δ) were collected in this plant. The residual fraction BB:Ci(Δ)-1 has a larger particle size. The residual fraction BB:Bd(Δ), on the other hand, was collected from the fines settling basin.

The ε (epsilon) mining company has two extraction sites: the Bonito mine, which extracts coal from the Bonito layer, and the G mine, where extraction is carried out from the Barro Branco layer (Fig. 2). The Bonito mine is beneficiated by jig and dense media where the residual fractions BO:Ji(ε) and BO:Md(ε), respectively, were collected. In mine G, the residual fractions collected are from the jig beneficiation of two discards identified as BB:Ji(ε)-1 and BB:Ji(ε)-2.

Finally, the mining company σ (sigma) extracts coal from the Bonito layer and concentrates the coal by jigging, resulting in a single residual

fraction identified as RE:Ji(σ) (Fig. 2).

2.2. Methods for materials characterization

A helium gas pycnometer model ULTRAPYC 1200e (Quantachrome Instruments, USA) was used to determine the specific mass of the 24 residual coal fractions. All of them were previously dried in an oven until constant mass and then comminuted till material passing a 16-mesh sieve (1.18 mm) was obtained.

The standard NM 248 (NM 248, 2003) was used to determine the particle size of the 24 residual fractions. The analysis was done by separating sieves with mesh openings of 150 μ m, 300 μ m, 600 μ m, 1.00 mm, 1.18 mm, 2.00 mm, 2.36 mm, 4.75 mm, 6.35 mm, 1.25 cm, 1.60 cm, and 2.50 cm. The different residual fractions were oven-dried at 105 ± 5 °C to constant mass, and the test was carried out in duplicate with 500 g of each material/test. Each fraction was submitted to mechanical agitation on a shaking table for 15 min to allow for the prior separation of the different particle sizes. Then, the mass of the material retained on each sieve was determined, and the percentage for each particle size range established by the sieve set used was calculated.

Oven drying of the residual fractions was used to determine the humidity at 100 ± 5 °C up to constant mass. The water absorption capacity of the different residual fractions in the saturated state with a dry surface was determined using the standard NM 30 (NM 30, 2001) using water at room temperature (~ 20 °C). The absorption capacity was calculated as a percentage of the sample's mass increase relative to its dry-state mass.

The pH of the solubilized waste was evaluated using an AK95 pH

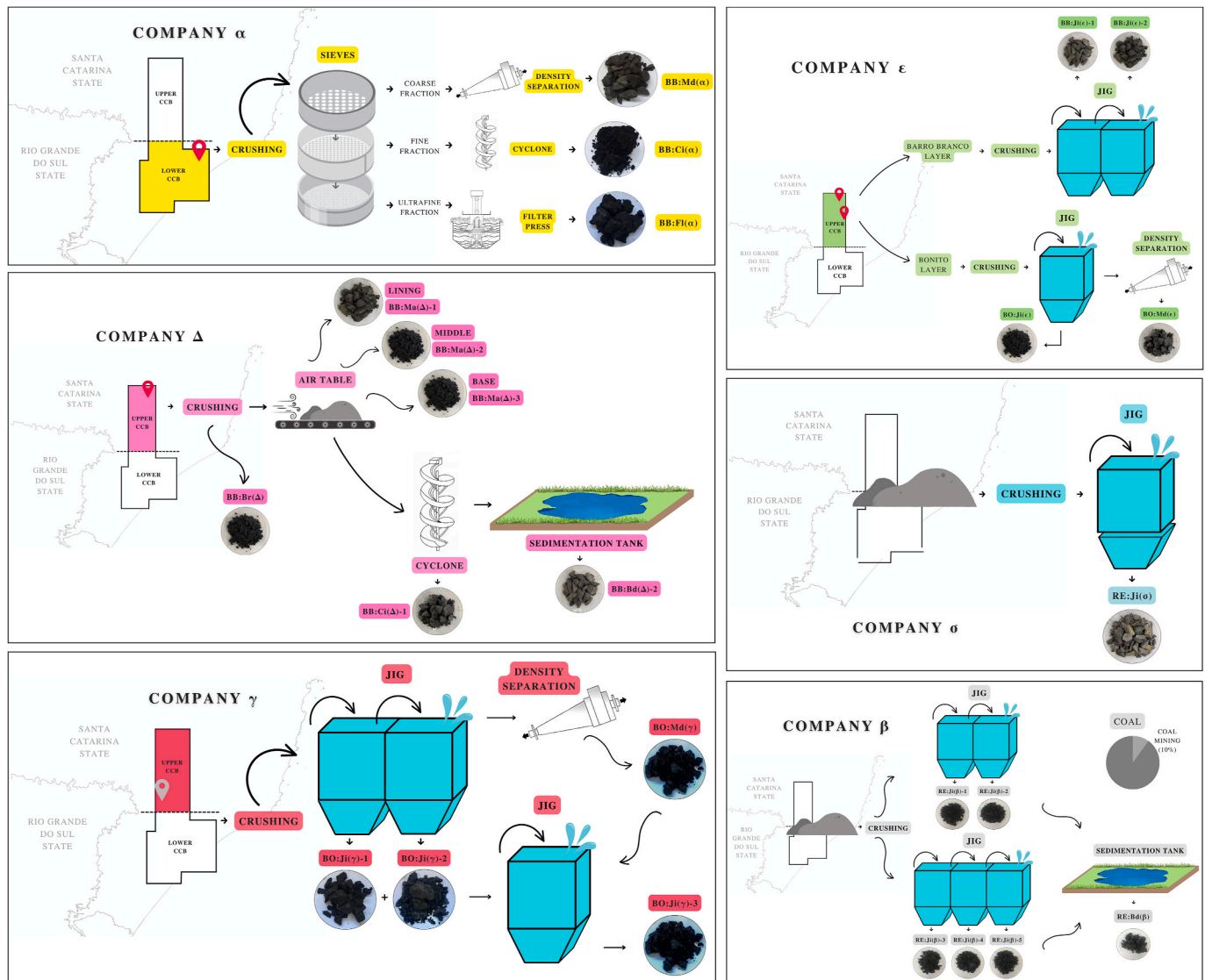


Fig. 2. Schematic representation of the different processing steps of mining companies and their respective residual fractions generated.

meter (AKSO, Taiwan). The pH reading was taken three times: immediately following the collection/preparation operation (within 24 h), after 12 months of conditioning in a closed container, and after 36 months of collection/storage. In a Becker cup, 4.0 g of each residual fraction (as formed, without drying) was mixed with 100 mL of deionized water for the analysis. A magnetic stirrer agitated the mixture for 15 min, followed by 5 min of rest.

The energy dispersive X-ray fluorescence (XRF) spectrometry (model EDX 7000, Shimadzu, Japan) was used to determine the chemical composition of the residual fractions. All samples were disaggregated with the aid of mortar and porcelain pestle until a 230 mesh (62 μm) sieve was passed. In this preparatory stage, 2 g of the 24 samples were separated from the residual fractions to perform the loss on ignition test (LoI). All those tests were performed in duplicate until 950 $^{\circ}\text{C}$, following the ASTM D7348 standard (D7348, 2008), to eliminate organic materials and constitutional water present. After the LoI, the ashes were ground and pressed into pellet form for further chemical analysis.

Mineralogical characterization was performed using X-ray diffraction (XRD). An X-ray diffractometer (model LabX XRD 6100, Shimadzu, Japan), with Cu radiation, tube voltage of 40 kV, and current of 30 mA, reading between 4 and 70 $^{\circ}$ (2 θ), and speed of 0.02 $^{\circ}$ /s was employed. The crystalline phases present were identified using the X'Pert High

Score Plus program.

For thermal characterizations of the residual fractions by thermogravimetric analysis (TG/DTG), the STA 449 F3 equipment (NETZSCH, Germany) was used in two steps. The first step was performed with a heating rate of 20 $^{\circ}\text{C}/\text{min}$ in an inert atmosphere (N_2) and 80 mL/min of flow, with approximately 70 mg of material, where the mass losses were determined by temperature variation. For the second step, the same residual fractions were weighed again and returned for thermal analysis equipment in an oxidizing atmosphere (compressed air) to mass loss determined. The experiment was carried out from 30 to 1100 $^{\circ}\text{C}$ for all samples.

2.3. Potential applications using coal mining residual fractions

After characterizing the samples, the residual fractions were organized based on their geological characteristics and waste processing methods. These groups were then linked to potential applications, which were proposed based on the characterization results and a thorough review of national and international literature. The literature review was conducted using the Scopus database and utilized keywords such as "coal mining waste," "coal tailings," and "coal gangue."

3. Results and discussion

3.1. Coal mining waste quantity generated in the study region

Since 1925, around 550 million tons of ROM have been treated in Brazil, with a waste generation of approximately 320 million tons. Fig. 3 shows statistics data on waste production from coal concentration in Santa Catarina from 1999 to 2021, as well as the cumulative amount (SIECESC, 2020).

According to SIECESC data (SIECESC, 2020), ROM extraction in Paraná, Santa Catarina, and Rio Grande do Sul was approximately 76 million tons between 2010 and 2015; 65% of the total ROM extracted became waste, resulting in 49.4 million tons of waste produced and accumulated by coal mining throughout the time (2010).

Fig. 4 shows many inactive waste sites (red) and eight active deposits (green) owned by BBC. Areas occupied by active wastes are 363.3 ha, while areas inhabited by inactive wastes are 1760.41 ha (SIECESC, 2022). Using data gathered from waste deposit sites and predicted height of area photos available on Google Earth (2022), this study projected the volume of waste in active deposits in the region at 58 billion m³.

According to information obtained from internal files of a regional mining company, approximately 65% of ROM extracted is deposited in a landfill as waste, with a monthly cost of transport and spreading (deposition) of ~ US\$42,000 plus the monthly monitoring of the waste deposit (including technical and recovery) of ~ US\$10,000, totaling monthly spending on landfill wastes of ~ US\$52,000.

However, mining companies are very interested in converting this waste into a new alternative material because the main issues are a physical area for waste disposal, transportation of the waste to the deposit, containment and isolation or waterproofing works, machinery for proper waste spreading, and generation and treatment of acid mine drainage (AMD). The cost of coal (end product) is determined by the ore recovery rate after beneficiation, which is a function of ore quality and product parameters.

The active deposit should be close to the ROM extraction to facilitate transportation and decrease deposition costs. Again, the eight active waste deposits were mapped and presented in the images shown in Fig. 5 through the Google Earth tool.

Waste deposits can take about 660 years to stop generating acidity (Amaral, 2014). Approximately 60% of the total mass of the waste corresponds to the clay fraction, totaling about 192 million tons, disposed of in waste modules. Added to this figure annually, 6 million tons correspond to the wastes from the extraction and processing of Brazilian coal (Amaral, 2014). The wastes deposited in landfills can be divided into fractions in descending order as to quantity: clay, pyrite, and carbonaceous. The fraction of a higher percentage (clayey) comprises siltstones, shales, and sandstones. It is related to its geological formation and temperature, having minerals of the silicate group (quartz, feldspars, and micas) and clays (Aguar et al., 2008). Table 2 shows the residual fraction resulting from each stage of the mines' processing, information collected during the visits, and the mass balances provided by the mining companies.

The extraction of the Barro Branco layer produces 86,000 tons of waste each month. The processing of the Bonito layer results in 95,000 tons of waste per month. Additionally, reprocessing old waste, which contains only 10% coal, generates 128,000 tons per month.

The Barro Branco layer provides better processing performance than the Bonito layer, as it is a larger basin with a homogeneous thickness (1.6–2 m). The Bonito layer has thin sheets of organic and inorganic matter with a lower yield in processing. This characteristic suggests a decrease in particle size to increase coal concentration (Kalkreuth et al., 2006).

The α -miner extracts 50,000 tons per month of ROM from the Barro Branco layer, generating 23,000 tons in the dense medium processing and 6000 tons in each fines processing (cyclone and flotation), totaling 35,000 tons of waste destined for landfills (70% of the ROM extracted). Adding the other units, the α mining company generates approximately 70 thousand tons/month of waste.

The β -mining company that benefits existing waste deposits through

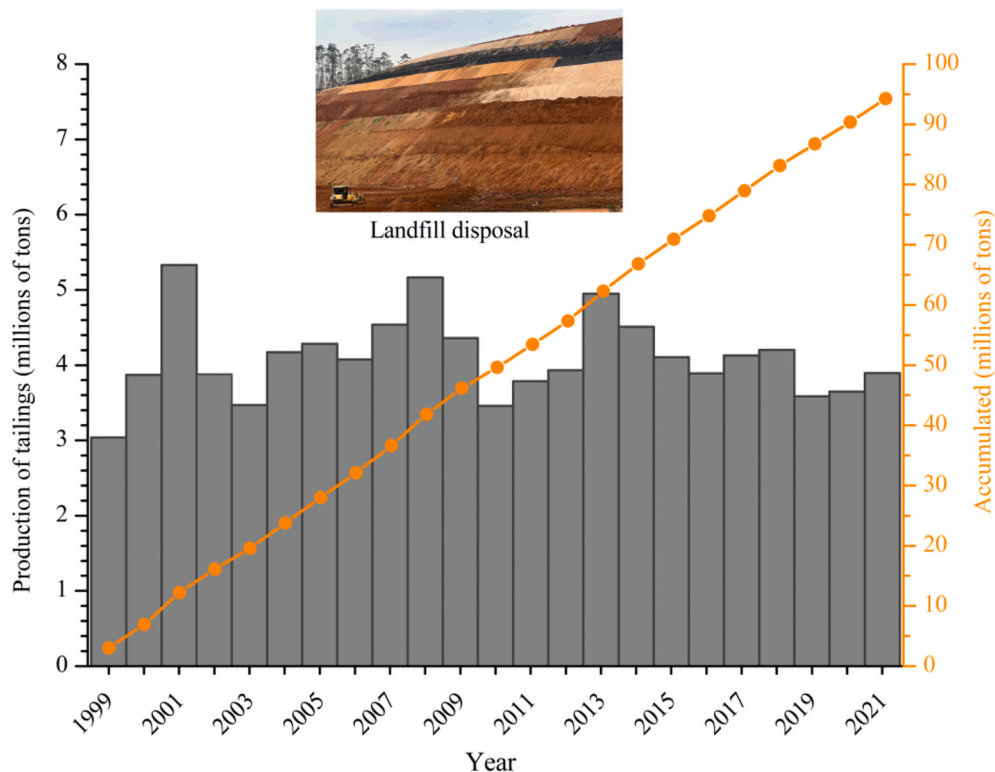


Fig. 3. Production and accumulated quantity of coal mining wastes generated in Santa Catarina in millions of tons.

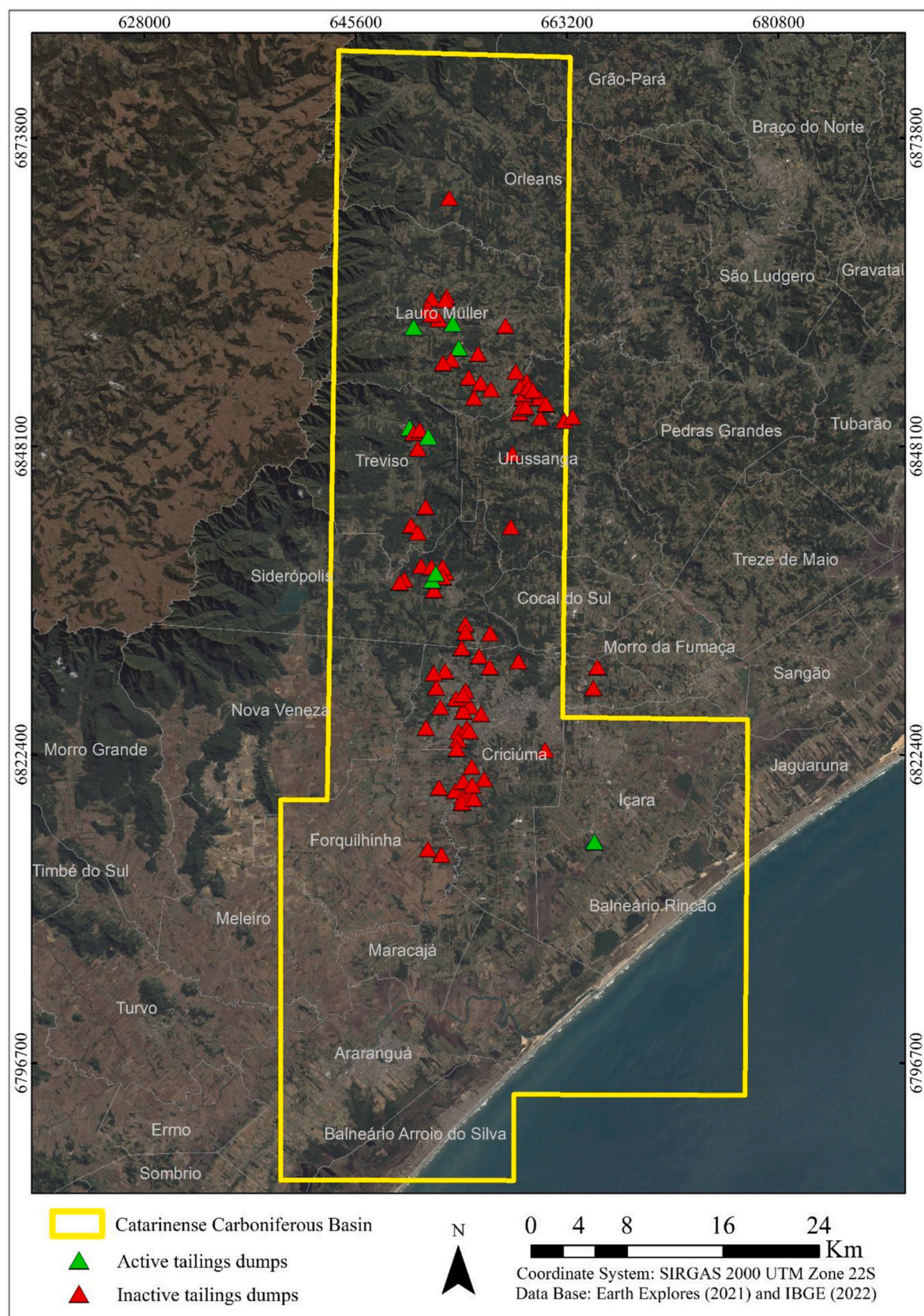


Fig. 4. The location map of active (green) and inactive (red) wastes deposits in the Santa Catarina coal basin. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

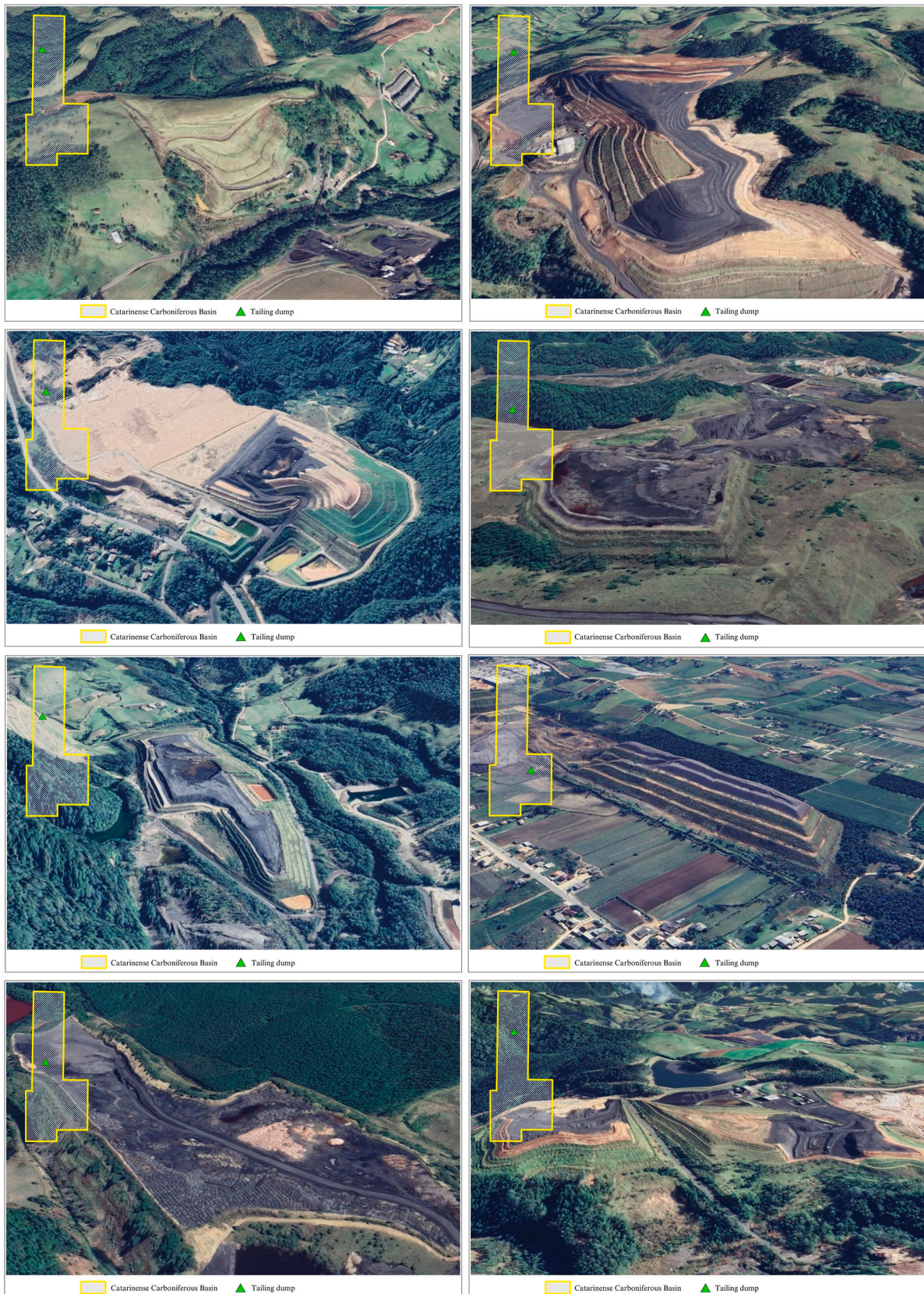


Fig. 5. Active waste dumps according to their location on the Santa Catarina coal basin.

Table 2

Amount of residual fractions generated monthly, separated by layers and re-beneficiation of the old waste dumps.

Layer	Code	Wastes Generation (thousand tons/month)
Barro Branco	BB:Md(α)	23.0
	BB:Ci(α)	6.0
	BB:Fl(α)	6.0
	BB:Ji(ϵ)-1	19.0
	BB:Ji(ϵ)-2	13.0
	BB:Ma(Δ)-1	11.0
	BB:Ma(Δ)-2	
	BB:Ma(Δ)-3	
	BB:Br(Δ)	5.0
	BB:Ci(Δ)-1	3.0
	BB:Bd(Δ)	
Bonito	BO:Md(γ)	29.5
	BO:Ji(γ)-1	10.0
	BO:Ji(γ)-2	5.5
	BO:Ji(γ)-3	Not disclosed
	BO:Ji(ϵ)	8.0
	BO:Md(ϵ)	42.0
Rejeito (reject deposits)	RE:Ji(β)-1	50.0
	RE:Ji(β)-2	
	RE:Ji(β)-3	
	RE:Ji(β)-4	
	RE:Ji(β)-5	
	RE:Ji(β)	78.0
	RE:Ji(σ)	
Total		309.0

jigging manages to concentrate 10% of coal and thus generates around 78 thousand tons of waste per month, which are then disposed of in landfills. The mining company that uses the Bonito layer generates a total of 45 thousand tons/month, of which only 29.5 thousand tons/month are discarded in the dense medium. The processing of ROM collected from the Barro Branco layer resulted in 32 thousand t/month at the mining company and 50 thousand t/month from the Bonito layer.

However, several studies (Acordi, 2022; Addou et al., 2017; Pashkevich, 2017; Taha et al., 2017) emphasize the importance of waste recovery when generated. The data presented here show that the study region has several mining wastes deposited in old landfills, with a large and still active generation of these materials. The generated data are essential for the applications studied to execute after evaluating the technical findings of the products and processes.

3.2. Characterization of coal mining residual fractions

3.2.1. Physical properties

The moisture content of the samples analyzed (Table 3) revealed that the large percentages are related to the coal concentration process, which in turn is associated with the particle size produced by each mining company's coal concentration method (different beneficiation processes). The most significant percentages of moisture discovered are between 65.26 and 14.30%, representing the highest fraction resulting from the cyclone and collected from the Barro Branco layer's settling basin - BB:Bd(Δ).

The residual fractions considered as fines in the analyzed processes (BB:Ci(α), BB:Fl(α), RE:Ji(β), BB:Ci(Δ)-1 and BB:Bd(Δ)), have demonstrably the smallest particle sizes in the results of the particle size distribution (Fig. 6) and higher percentages of moisture. It is important to emphasize that these fine materials are forwarded to the deposits as "sludge", which justifies the high rates of water content in the samples. Relating the process and percentage of moisture, it is clear that the highest levels of moisture are from the fractions that came out of the cyclone (BB:Ci(α), BB:Ci(Δ)-1), flotation step (BB:Fl(α)); and settling basin (BB:Bd(Δ), (RE:Bd(β)).

The processing to which the ROM is submitted is, as expected, related to the particle size of the waste fractions. As a result, an examination of the particle size distribution associated with the type of processing to which the ROM was submitted is performed below. The coarse waste particles (between 50.8 mm and 2.0 mm) will be presented (Sampaio and Tavares, 2005). The particle size distribution of the residual fractions from the crusher, jig, dense medium, and air table are shown in Fig. 6. The following fractions are categorized as fine (2.0 mm–0.5 mm) and ultrafine (below 0.5 mm) from the process of coal concentration by the cyclone: BB:Ci(α), BB:Ci(Δ)-1; Flotation: BB:Fl(α)

Table 3

Moisture data, specific mass, and water absorption of the residual fractions.

Layer	Waste Code	Moisture (%)	Density (g/cm ³)	Water Absorption (%)
Barro Branco	BB:Md(α)	3.98	2.54	3.20
	BB:Ji(ϵ)-1	3.17	2.51	1.30
	BB:Ji(ϵ)-2	4.59	2.38	1.20
	BB:Ma(Δ)-1	6.71	2.77	7.30
	BB:Ma(Δ)-2	6.04	2.33	4.90
	BB:Ma(Δ)-3	1.25	3.18	2.80
	BB:Br(Δ)	14.30	2.36	7.60
	BB:Ci(α)	14.88	2.53	3.90
	BB:Ci(Δ)-1	20.39	2.40	5.40
	BB:Bd(Δ)	65.26	2.43	12.30
	BB:Fl(α)	18.64	2.14	10.30
Bonito	BO:Md(γ)	3.31	2.30	1.70
	BO:Md(ϵ)	6.21	2.65	
	BO:Ji(γ)-1	2.94	2.61	Not Measured
	BO:Ji(γ)-2	2.87	2.73	
	BO:Ji(γ)-3	3.78	2.85	
	BO:Ji(ϵ)	16.30	2.64	
Rejeito	RE:Ji(β)-1	6.22	2.58	0.80
	RE:Ji(β)-2	6.96	2.45	1.70
	RE:Ji(β)-3	6.43	2.82	Not Measured
	RE:Ji(β)-4	10.89	2.50	2.30
	RE:Ji(β)-5	9.90	2.43	3.30
	RE:Bd(β)	20.42	2.38	9.40
	RE:Ji(σ)	4.80	2.34	3.90

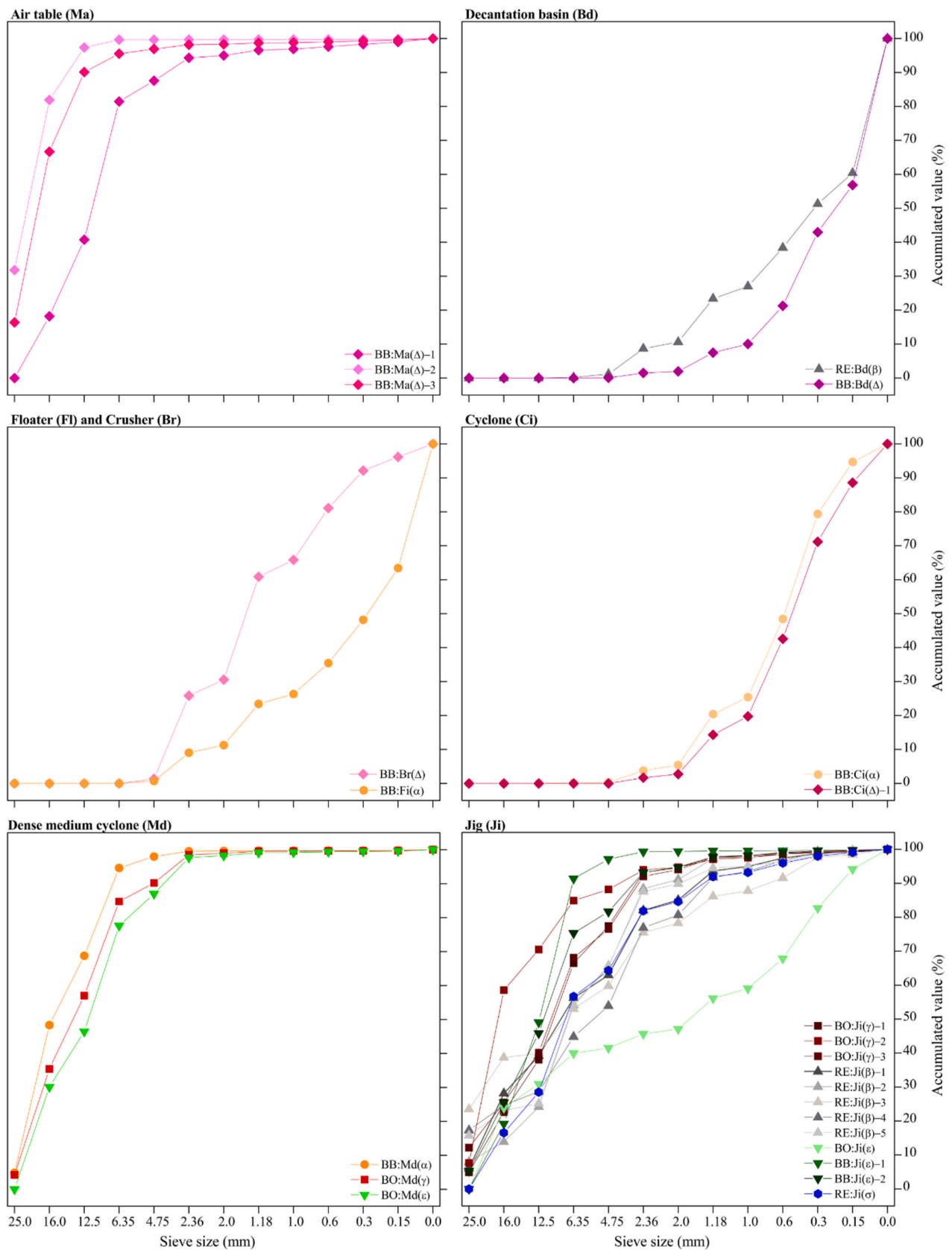


Fig. 6. Cumulative particle size distribution of the residual fractions resulting from the different processing.

and settling basin: RE:Bd(β) and BB:Bd(Δ). These fractions were thus categorized according to Sampaio and Tavares' categorization (Sampaio and Tavares, 2005).

A variation of 2.14–3.18 g/cm³ can be observed by analyzing the specific mass of the residual fractions (Table 3). Specific mass values between 2.30 and 2.50 g/cm³, close to those in this study, are found in the literature (Skarżyńska, 1995). To perform correlations, it is important to consider that the coal has a specific mass between 1.30 and 1.50 g/cm³, the mineral fraction that accompanies it between 2.65 and 2.70 g/cm³, and the pyrite fraction between 4.90 and 5.10 g/cm³ (Ruiz, 2009). Specific mass values of the clay fraction contained in the wastes are also found between 2.50 and 2.70 g/cm³ (Amaral, 2014). Therefore, these characterizations and information strengthen the hypothesis that most of these materials are formed by clay minerals. However, it is believed that the specific mass values above this range may be associated with the simultaneous presence of some pyrite.

The water absorption analysis of the residual fractions (Table 3) reveals that the three fractions with the highest absorption rate are residues regarded as fine in the processing, BB:Bd(Δ), BB:Fl(α), and RE:Bd(β), with 12.3; 10.3; and 9.4%, respectively. It is highlighted that higher absorption values are connected with higher clay content because clay particles have smaller particle sizes than silts and sands. Water molecules and other ions, dissolved in the spaces between the layers of these clay minerals, may occupy these spaces (Pozzi and Galassi, 1994).

It is possible to relate the carbon content of a waste knowing its specific mass because the lower the specific mass, the higher the presence of carbon (Vo et al., 2022). Thus, the sample BB:Fl(α) has a lower specific mass among the residual fractions, is due to the fact of the more significant presence of finely dispersed coal in the material, resulting from the flotation stage process of the Barro Branco layer, information confirmed by the thermal characterization (Fig. 7). This same relationship can be made for the residual fraction, BB:Ma(Δ)-3, with higher specific mass (3.18 g/cm³) and consequently a lower percentage of coal. Regarding the chemical composition (Table 4), the most increased specific mass also has the highest iron content (Fe₂O₃). In the beneficiation fractions from old waste deposits, we found the highest specific mass with the highest percentage of Fe₂O₃ (RE:Ji(β)-3).

3.2.2. Thermal analysis

The TG and DTG results of thermal characterization are plotted in Fig. 7 and were carried out with one specimen of each group in an inert atmosphere (N₂) followed by burning in an oxidizing atmosphere (compressed air). The thermograms obtained in the oxidizing atmosphere show the mass loss after all mass losses occurred in the nitrogen

atmosphere (the first thermogravimetric analysis). This justifies that the mass loss in the second thermogravimetric analysis (oxidizing atmosphere) does not start at the zero point. In general, it is observed that the thermal behavior of the samples presents differences, reinforcing the hypothesis of this research focused on the particularity of the characterizations of each group with the possibility of valorization. Group 1 represents the BB:Fl(α) fraction with the most significant mass loss. In their work, Zhang and Ling (2020) highlighted that the more significant loss on ignition observed in other coal waste samples suggests higher carbon content. Group 2, represented by the fraction BO:Md(γ), group 4A, represented by the fraction BO:Md(ϵ), and Group 4B, represented by the fraction BO:Ji(γ) - 2, have an illitic mineralogical nature. In the thermograms of these groups, we observed endothermic events with broader peaks in an oxidizing atmosphere, suggesting the presence of clayey from the illite group (Gomes, 1986). Group 3A and 3B, formed mainly through clays of kaolinite origin, present a mass loss at approximately 500 °C due to kaolinite decomposition (release of constitution water) and the formation of metakaolinite (De Almeida Azzi et al., 2016; Nieto et al., 2008; Zhang and Ling, 2020). Another mineral identified in the thermogravimetric analysis was the pyrite. According to Peterson et al. (2008), pyrite has a characteristic mass loss peak of around 600 °C related to thermal decomposition for the formation of pyrrhotite (FeS) and sulfur evaporation (S₂). The reaction must be accompanied by a mass loss ramp, as occurs in groups 1, 2, 3A, 3B, and 4A, suggesting the presence of pyrite minerals in those five groups.

3.2.3. Chemical and structural composition

The chemical composition results (Table 4) were organized by the layers of coal extraction: Barro Branco, Bonito, and old waste deposits. Silicon oxides (SiO₂: varies from 49.77 to 8.20%), alumina (Al₂O₃: 23.77 to 3.39%), sulfur (SO₃: 10.78 to 0.13%), iron oxide (Fe₂O₃: 46.68 to 2.87%), and potassium (K₂O: 4.54 to 0.34%) make up the majority of residual fraction oxides. The only exception is the residual fraction BB:Ma(Δ)-3, which results from dry processing by air table and comes from the Barro Branco layer's Banco sub-layer, which contains 8.20% SiO₂ and 3.30% Al₂O₃. This fraction has the most iron oxide (Fe₂O₃ - 46.68%) and the most extensive ignition loss (41.05%).

Because of the high silica and alumina concentration in the remaining fractions, the ash produced by thermal treatment of coal waste has a high melting temperature ranging from 1050 to 1800 °C and can be used as a refractory raw material (Li and Wang, 2019).

Analyzing the loss on ignition of all fractions (Table 4), one can notice a variation of 15.25% for lower loss on ignition and 41.05% for fractions for the higher loss on ignition. These percentages are due to the

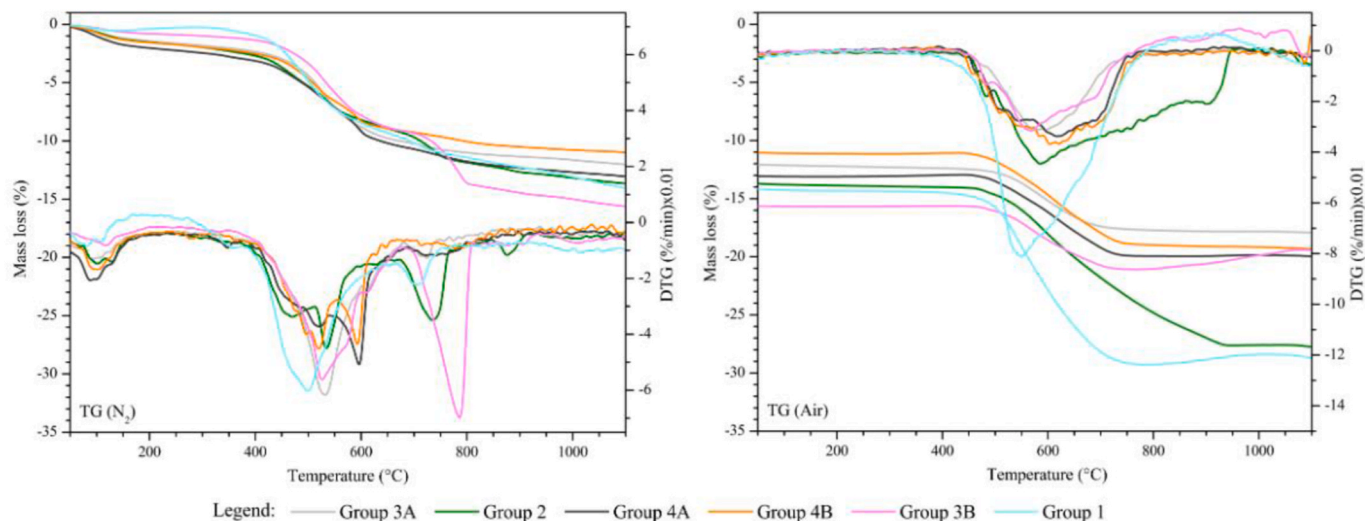


Fig. 7. Thermal analysis plots, TG and DTG in different atmospheres (N₂ and air), of six residual fractions.

Table 4
Chemical composition of the residual fractions (XRF).

Layer	Sample	Oxide (% weight)											
		SiO ₂	Al ₂ O ₃	SO ₃	Fe ₂ O ₃	CaO	K ₂ O	TiO ₂	MgO	MnO	ZrO ₂	others	Loss on ignition
Barro Branco	BB:Md(α)	49.62	20.82	0.60	6.69	1.52	2.83	1.60	0.00	0.01	0.06	0.20	16.04
	BB:Ji(ε)-1	44.61	20.55	0.13	12.76	0.35	2.66	1.38	0.00	0.02	0.06	0.15	17.33
	BB:Ji(ε)-2	47.00	23.77	0.14	5.96	0.43	3.18	1.58	0.00	0.02	0.04	0.22	17.66
	BB:Ma(Δ)-1	29.23	14.47	0.14	18.32	0.07	1.29	0.70	0.00	0.01	0.05	0.08	35.65
	BB:Ma(Δ)-2	40.38	17.96	0.13	12.54	0.00	1.79	1.04	0.00	0.01	0.05	0.09	26.02
	BB:Ma(Δ)-3	8.20	3.39	0.14	46.68	0.08	0.34	0.00	0.00	0.00	0.01	0.12	41.05
	BB:Br(Δ)	49.77	22.82	0.14	2.87	0.00	2.47	1.57	0.00	0.02	0.08	0.19	20.09
	BB:Bi(α)	36.73	16.11	1.89	11.28	7.65	2.32	1.35	0.00	0.04	0.05	0.23	22.36
	BB:Bi(Δ)-1	40.59	17.38	0.27	10.11	0.24	1.74	0.97	0.00	0.01	0.05	0.16	28.47
	BB:Bd(Δ)	47.87	22.03	1.19	3.20	0.97	2.25	1.37	0.72	0.01	0.06	0.13	20.20
Bonito	BB:Fl(α)	41.15	20.15	0.34	3.08	0.96	1.99	1.03	0.39	0.01	0.04	0.07	30.80
	BO:Md(γ)	36.36	12.74	10.78	8.39	6.40	3.89	1.06	0.47	0.16	0.04	0.18	19.54
	BO:Md(ε)	47.16	18.00	0.48	11.73	0.96	4.44	1.09	0.64	0.03	0.04	0.17	15.25
	BO:Ji(γ)-1	37.88	13.41	3.71	18.72	2.12	3.06	0.70	0.50	0.06	0.03	0.07	19.75
	BO:Ji(γ)-2	37.48	13.86	10.2	12.61	5.36	3.61	0.80	0.00	0.15	0.04	0.20	15.68
	BO:Ji(γ)-3	47.57	16.83	1.71	10.07	1.16	4.54	0.95	0.53	0.04	0.04	0.09	16.47
	BO:Ji(ε)	37.35	13.77	0.91	18.01	2.11	3.30	0.78	0.00	0.08	0.06	0.23	23.39
Rejeito (reject deposits)	RE:Ji(β)-1	42.45	16.93	4.35	8.75	2.14	2.67	1.40	0.00	0.01	0.06	0.08	21.15
	RE:Ji(β)-2	40.50	18.14	4.30	9.85	2.62	2.61	1.33	0.00	0.02	0.07	0.16	20.4
	RE:Ji(β)-3	35.54	15.73	2.21	16.85	1.16	2.03	0.98	0.00	0.01	0.09	0.16	25.23
	RE:Ji(β)-4	45.27	16.93	3.05	5.36	1.76	2.47	1.23	0.00	0.01	0.07	0.16	23.68
	RE:Ji(β)-5	40.28	14.93	4.82	7.99	2.28	2.68	1.31	0.00	0.01	0.06	0.12	25.5
	RE:Bd(β)	43.20	17.22	0.78	8.54	0.66	3.13	1.32	0.00	0.01	0.05	0.18	24.91
	RE:Ji(σ)	39.34	15.26	2.50	10.67	5.04	3.47	0.98	0.50	0.09	0.00	0.18	22.00

water constitution loss of the clay minerals, the hydration of ferrous sulfate, the oxidation of organic matter (carbonaceous fraction still existing in the residual fractions), the decomposition of carbonates, such as calcite (CaCO₃), and the decomposition of pyrite, starting at 600 °C (Gomes, 1986; Peterson et al., 2008). These reactions occur in all fractions, with greater or lesser intensity. A carbonaceous material content (volatile during combustion) higher than 20% can be used in a certain percentage in a circulating fluidized bed combustion (Li and Wang, 2019). The highest rates of loss on ignition are from the company Δ whose residual fractions, BB:Ma(Δ)-1 Forro sub-layer, BB:Ma(Δ)-2 Quadração sub-layer, BB:Ma(Δ)-3 Banco sub-layer and BB:Bi(Δ)-1, can hardly be compared with the others because it is selective mining where the Barro Branco layer outcrops and its extraction takes place in an open-cast mine. Another residual fraction that presents a high loss on ignition percentage is the company α (BB:Fl(α)) with 30.8%. However, it can be seen that all fractions belong to the Barro Branco layer.

Fe₂O₃ and TiO₂ oxides (0.70–1.60%, Table 4), known as chromophore oxides, are present in all residual fractions except for sample BB:Ma(Δ)-3, which lacks TiO₂ but has the highest proportion of iron. The iron content appears in the XRF as Fe₂O₃, but it is also partially related to the material's pyritic content (FeS₂), further defined through mineralogical investigation, presented in Fig. 8, and discussed in more detail later.

Based on the chemical analysis, Table 4, it is observed that all the residual fractions of this study present a higher percentage of SiO₂ than Al₂O₃. Fig. 9 shows the residual fractions' silica and alumina content and the Al₂O₃/SiO₂ ratio. It can be observed that the Al₂O₃/SiO₂ ratio varies between 0.35 and 0.50. Thus, three classes are defined. The first class comprises the highest SiO₂ percentages, where the Al₂O₃/SiO₂ ratio <0.3. In this class, the main mineral compounds are quartz and feldspar, and those samples have low plasticity due to the lower clay mineral content and the largest particle size. The second class presents an Al₂O₃/SiO₂ ratio between 0.3 and 0.5 and is mainly composed of

kaolinite and illite, besides a small amount of quartz, feldspar, and calcite. For the third class (Al₂O₃/SiO₂ > 0.5), the mineral composition is mainly formed by kaolinite with a fine average diameter, allowing a more remarkable plasticity. In this sense, this sample class can be used as a raw material for ceramic manufacturing (Li and Wang, 2019).

Analyzing the geological coal seams that give rise to the residual fractions in this study, the Barro Branco layer is formed by bituminous coal beds with high pyrite content intercalated with carbonaceous siltstones and shales. The Bonito layer is formed by coal beds separated by a layer of waste material and consisting of siltstones, shales, and sandstones (Kalkreuth et al., 2010; Suffert et al., 1977). However, the residual fractions in this study from the Barro Branco layer have an Al₂O₃/SiO₂ ratio ranging from 0.50 to 0.41 and, therefore, fall into the second class (kaolinite and illite minerals with Al₂O₃/SiO₂ ratio between 0.3 and 0.5), thus tending to have more clayey behavior. The fractions of the Bonito layer (0.38–0.35) also fall into the second class but close to the first class (Al₂O₃/SiO₂ ratio <0.3) and, consequently, with a tendency to behave identically to a sandy material. The Al₂O₃/SiO₂ ratio is 0.37–0.44 and is characterized as second class (kaolinite and illite minerals) for the fractions resulting from reworking old waste deposits.

The sulfur (SO₃) presence can also be found in all fractions (Table 4). This is justified because the coal in the region is paralytic (connected to the sea). As a result, it has more significant sulfur content due to the marine effect and sulfates. Sulfur is found in minor amounts in the organic portion of coal, but it is present mainly in the inorganic fraction as the mineral pyrite, the most abundant sulfur in coal. Due to sulfur reduction in marine waters, pyrite can occur as a primary detrital mineral or as autogenic (secondary pyrite) (Simão, 2016). Gravity separation may extract sulfur from ROM coal beneficiation residual fractions with SO₃ content higher than 6% (Fan et al., 2014). The residual fractions that correspond to these higher sulfur contents in this study are BO:Md(γ) (SO₃ = 10.8%) and BO:Ji(γ)-2 (SO₃ = 10.2%).

Carbon, nitrogen, and hydrogen are present in organic matter. The

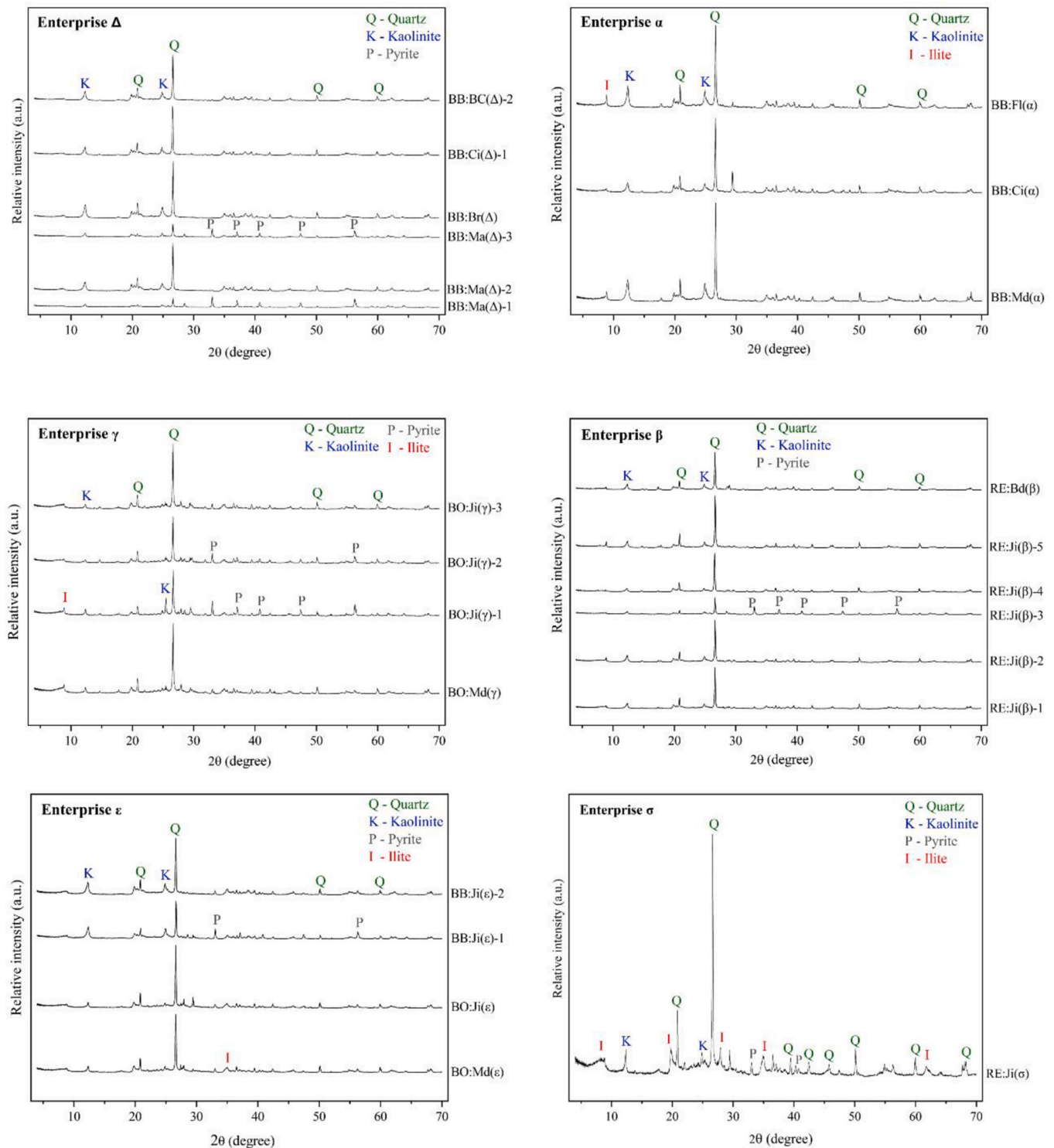


Fig. 8. XRD of residual fractions.

carbon comes from the organic matter, and the hydrogen comes from the water, constituting the clay minerals and the hydration of ferrous sulfate. The high percentage of ash (84.38–69.12%) is expected since the analyzed residual fractions contain some coal concentrations from the ROM and have high levels of inorganic (unburnable) materials. Still on the elemental chemical analysis, as already commented, it can be observed that the fractions BO:Md(γ) and BB:Fl(α) have the lowest specific masses, 2.30 and 2.14 g/cm³ (Table 3), respectively, and contains greater amount of carbon, nitrogen, and hydrogen and can be used

in mixtures with coals of better quality or other industrial waste with energy potential (Barbosa et al., 2009; Hu et al., 2006; Muthuraman et al., 2010).

The identification of the mineralogical phases present in the residual fractions is shown in Fig. 8. For the residual fraction BB:Ji(ε)-1, the beneficiation process can justify the presence of pyrite. This fraction represents the result of the jig's first discard. This technique, which separates the ROM into fractions, will release more material of higher density in the first disposal, leading to a significant occurrence of pyrite

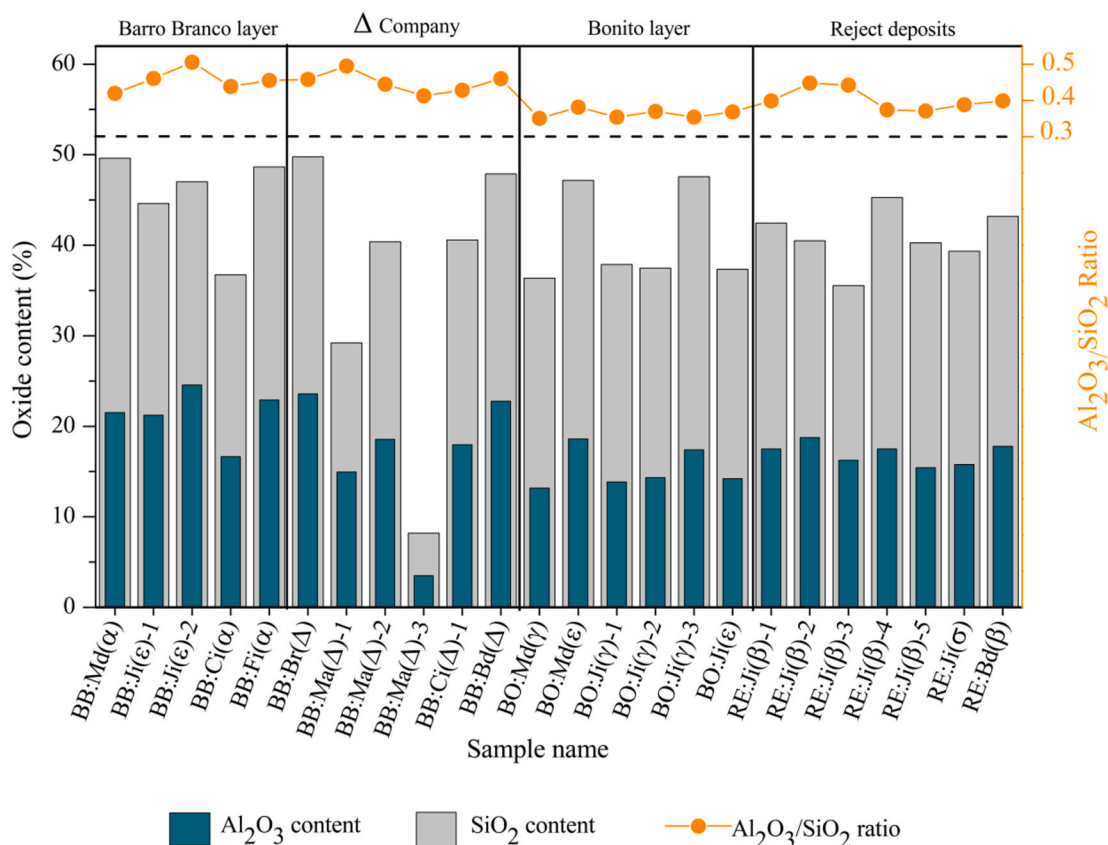


Fig. 9. Alumina, silica oxide content, and Al₂O₃/SiO₂ ratio of the residual fractions.

in this fraction. Another fraction of the Barro Branco layer with pronounced pyrite peaks is the fraction BB:Ji(ε)-2, which result establishes a similarity with the investigation carried out by the work of Kalkreuth et al. (2010), who detected a higher presence of sulfur, primarily pyritic, in the Barro Branco layers than in the Bonito layer (Kalkreuth et al., 2010).

As previously mentioned, the residual fractions BB:Ma(Δ)-1 and BB:Ma(Δ)-3 are extracted in open-cast mining of the Barro Branco layer and processed dry. Thus, the mining is selective, where the visual characteristics of the ROM are analyzed, and the layers of interest for coal concentration are selected. In these fractions, the pyrite phase appears in well-defined peaks that can be compared with the quartz peaks. The pronounced pyrite peaks of these fractions can be discussed according to Kalkreuth et al. (2010), which indicated in their studies a higher pyrite content in the coal samples from the Forro and Banco sub-layers of the Barro Branco layer, to which the fractions BB:Ma(Δ)-1 and BB:Ma(Δ)-3, respectively, belong (Kalkreuth et al., 2010). Another characterization that shows similarities with the results discussed by Kalkreuth et al. (2010) is the presence of iron oxide (Fe₂O₃), which is associated with the presence of the mineral pyrite, and in the chemical analysis of the samples BB:Ma(Δ)-1 and BB:Ma(Δ)-3 with percentages of 18.32 and 46.68%, respectively (Kalkreuth et al., 2010).

The chemical composition of the residual fractions agrees with the thermal analyses, Fig. 7, and the mineralogical phases of the residual fractions present in this study, Fig. 8. The clay phases, identified as illite and kaolinite, mainly define the mineralogy composition of the residual fractions. The XRD results confirmed that all fractions have the presence of quartz. Previous studies with coal waste have identified quartz and kaolinite as the main phases (Oliveira et al., 2021). According to Kalkreuth et al. (2010), the presence of kaolinite and quartz was also verified in ROM and coal samples from the southern region of Santa Catarina (Kalkreuth et al., 2010).

The mineralogical analysis identified the illite phase and confirmed it in the thermal analysis as being more constant in the fractions resulting from the processing of the Bonito layer. Coal processing residues are formed by minerals belonging to sedimentary rocks rich in silicon and aluminum oxide generally hydrated, including quartz, kaolinite, illite, feldspars and potassium, mica, carbonates, and sulfides (Vo et al., 2022).

The residual fractions BO:Ji(γ)-2 and BO:Ji(γ)-1 generated by coal processing from the Bonito layer show significant pyrite peaks that converge with the chemical analyses, with Fe₂O₃ percentages of 12.61% and 18.73%, respectively. The mineralogical examination of the RE:Ji(β)-3 fraction also shows significant pyrite peaks, which may be related to the high amount of iron oxide (16.85%) in the chemical analysis.

The residual fraction RE:Ji(σ) is the only fraction resulting from the beneficiation of former waste deposits of the company σ, and its mineralogical analysis presents peaks of the minerals expected to coal wastes from the southern Santa Catarina region deposited in landfills.

The residual fractions in this study agree with the characteristics of the waste studied by researchers Cutruneo et al. (2014), where quartz (SiO₂) identified by X-ray diffraction and clay minerals such as kaolinite (Al₂O₃·2SiO₂·2H₂O) are part of the composition of coal mining wastes.

Fig. 10 presents the pH values of the residual fractions in three different periods: in the moment of collection, 12 and 36 months after collection. It can be observed that most of the residual fractions undergo acidification over time. Analyzing the pH of the waste when collected, it can be observed that five of these presented a pH greater than 7, characterizing as basic material: (BB:Md(α) - 7.74; BO:Ji(ε) - 8.2; BB:Cl(α) - 7.95; BB:Fl(α) - 7.53; BB:Cl(Δ)-1 - 8.5). A common feature is that they are fine wastes, except for sample BO:Ji(ε). In general, the fine wastes undergo several washing processes for coal concentration, which may explain higher clay concentration and more significant removal of pyrite material, resulting in a higher pH. Two residual fractions belonging to

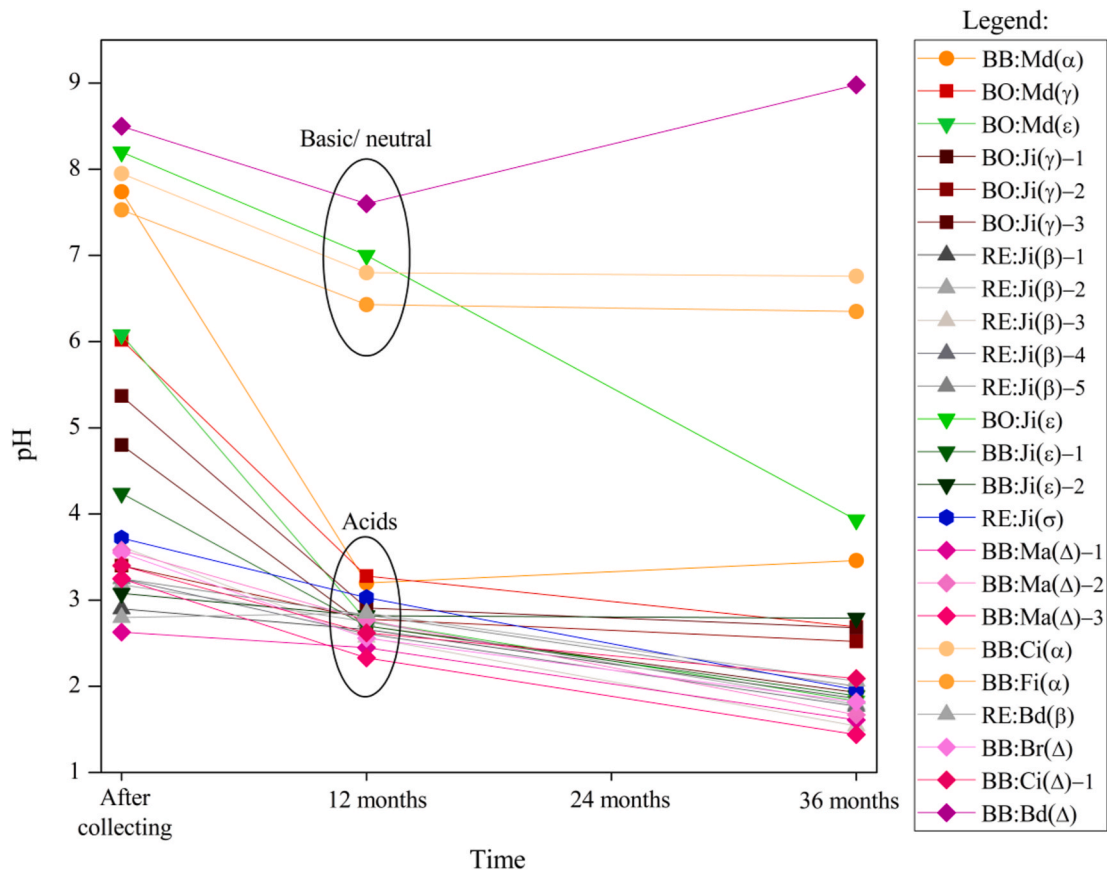


Fig. 10. Samples pH in three different periods: after collection, 12 months after collection, and 36 months after collection.

the Bonito layer and resulting from the processing by the dense medium of different companies showed neutral pH (BO:Md(γ) - 6.02 and BO:Md(ϵ) - 6.08). Finally, the other 17 wastes showed a pH between 5.37 and 2.63; therefore, they were classified as an acid material. When the pH of the remaining acidic fractions is compared to their granulometry, it is clear that these fractions are composed of 70% particles larger than 2.36 mm, except BB:Br(Δ). Analyzing the mining companies' processing in general in this study, it can be seen that the first residual fractions discarded in the coal concentration are formed by materials with larger

particle size, higher specific mass, and higher pyrite contents, which helps to justify pH values below 3.0.

After 12 months of storage, all residual fractions decreased in pH, except for the RE:Ji(β) wastes, which had a modest increase at 12 months (2.80–2.85) but decreased at 36 months.

The acidification trend continued after 36 months of storage, with 50% of the fractions having a pH below 2, which, according to standard NBR 10004 (NBR 10004, 2004), identified as hazardous waste. The chemical composition of the residual fractions has not changed during

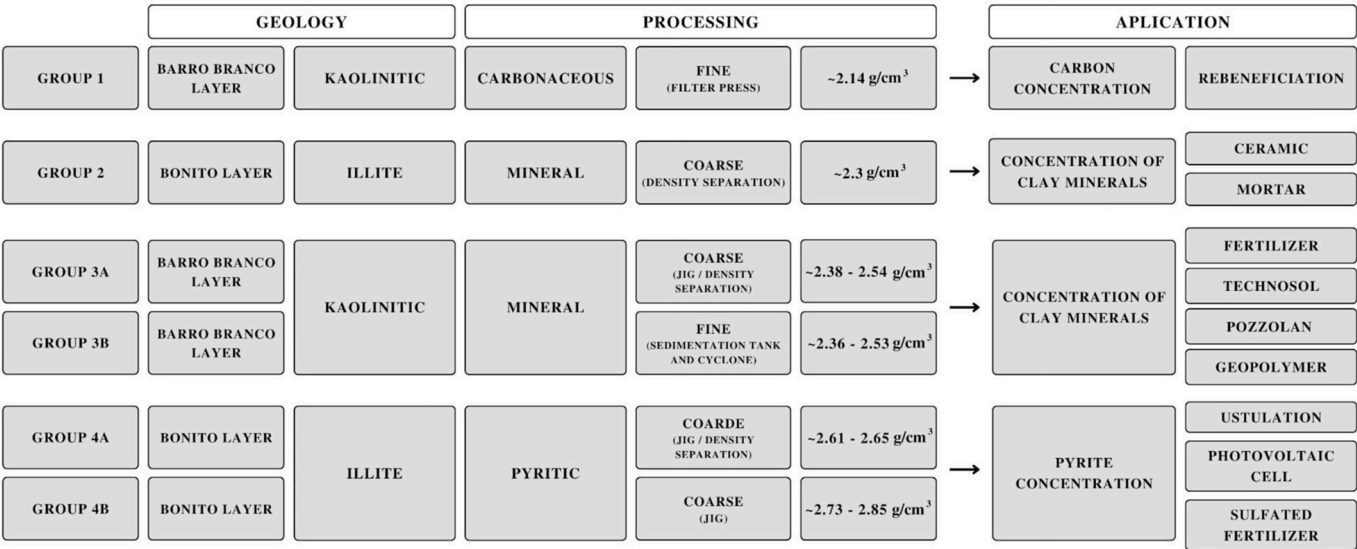


Fig. 11. The six groups from applications of residual fractions resulting from the analysis of geology nature and the beneficiation processes used.

this storage time, implying that the change in pH is due to a change in the wastes' chemical structure.

The observations of pH behavior advise the use and valorization of the waste soon after its generation because, with time passage, it becomes a material that cannot be reused, following Brazilian legislation.

3.3. Waste valorization through applications in new processes and products

Fig. 11 shows associations for potential applications of waste residual fractions discharged during ROM processing by mining companies in Santa Catarina's southern region. These interactions are intimately linked to the geology (coal layers) and ROM processing.

Coal deposits mined commercially in the region include the Barro Branco and Bonito seams, which have geological characteristics of origin. The residual fractions eliminated will have distinct granulometry depending on the processing (equipment type, number of stages, and technology utilized). Fine residual fractions, for example, are typically composed of silts and clays. The initial residual fraction discarded in the jig contains more pyrite than the other discards made during the beneficiation cycle. A certain granulometry is necessary for each processing method to recover the most significant proportion of coal. Six groups were developed to associate prospective applications for the residual fractions based on the geological character provided by the nature of coal and its processing.

Group 1 is formed by the fraction BB:Fl(α) presented specific mass (Ruiz, 2009) and loss of ignition that can be associated with higher carbon content. It was possible to assess that a residual fraction from the Barro Branco layer, with adequate specific mass and discarded in the flotation process, can be destined for processing and carbon concentration. The carbon concentration from coal mining waste and backfill mining is a practice made by local mining. It provides promising solutions to sustainability, which is also supported by other studies from the literature (Yu et al., 2025).

The residual fraction that characterizes group 2 is BO:Md(γ), with geological characteristics that indicate it belongs to the Bonito layer (illitic clay), and therefore, the ROM of origin for a better concentration of coal needs to use the dense medium operation. It has minor pyrite in its constitution, resulting in low specific mass. Its granulometry is characterized as coarse, with neutral pH, and can be used to concentrate clay minerals for use in ceramics (Rebello et al., 2024) and mortars (Acordi et al., 2023). Rebello et al. (2024) conducted a study on the use of CMW in clay ceramic formulations in the studied region. The authors compared their results with a reference ceramic formulation from the local productive arrangement, Cerâmica Vermelha de Morro da Fumaça. The findings demonstrated that incorporating a residual mining fraction into the formulation of clay ceramics is beneficial for promoting a circular economy in the regional mineral sector, resulting in both productive and environmental gains (Rebello et al., 2024). Some studies have explored using calcined or activated CMW to formulate various cement products. Acordi et al. (2022) provide a more in-depth discussion of its applications, including its use as a pozzolan, in bricks, and as aggregate for mortars. While it is essential to consider certain limitations of these applications, some uses—such as decorative arts in interior spaces or architectural elements—do not require high-performance properties. In these cases, the pigmentary elements present in the waste can be effectively utilized (Acordi et al., 2023).

To concentrate the clay minerals present in the fractions of the Barro Branco layer, group 3 was divided into 3A, with the fractions resulting from the processing by jig or dense medium, and 3B, fractions resulting from the cyclone and settling basin processing. Differences between the fractions belonging to groups 3A and 3B are given from processing, resulting in fractions considered coarse for group 3A and fine for group 3B. These groups are suggested for use in fertilizers and techno-soils (Olivo et al., 2024), pozzolans, and geopolymers (Simão et al., 2023) due to the concentration of the clay minerals. The residual

fractions associated with group 3A were: BB:Ji(ϵ)-1, BB:Ji(ϵ)-1, BB:Md(α) and for group 3B: BB:Br(Δ), BB:Bd(Δ) and BB:Cl(α). The fraction BB:Br(Δ) resulting from selective mining is the only one that has crusher processing, but as its characteristics fit into this group, it had this reference. Olivo et al. (2024) investigated the feasibility of using a combination of residual coal waste, byproducts from the rice and poultry agro-industries, and waste from the cellulose industry as raw materials for developing technosols. The chemical and physical characterizations confirmed that the residual fraction of ROM coal has the potential for use in technosol formulations by the legislation of Santa Catarina state. Ecotoxicity tests indicated that the soil was non-toxic to plants across all treatments studied (Olivo et al., 2024). Simão et al. (2023) developed geopolymers using (CMW). The findings indicated the potential for utilizing CMW in geopolymer formulations, with thermal curing proving to be an effective method for enhancing the reactivity of the waste (Simão et al., 2023).

Group 4 with geological characteristics can be classified as illite fractions (with greater incidence for the Bonito layer) and pyritic due to the beneficiation for coal concentration (densimetric). This association of characteristics suggested the separation in group 4A with the average specific mass of 2.61–2.65 g/cm³ and resultant in the beneficiation by jig or dense medium, and group 4B resultant of the beneficiation by jig presenting higher specific mass between 2.73 and 2.85 g/cm³. The residual fractions associated with group 4A were: BO:Ji(γ)-1, BO:Ji(ϵ), and BO:Md(ϵ), and the fractions of group 4B were BO:Ji(γ)-2, BO:Ji(γ)-3 and RE:Ji(β)-3. Because of the similarities in their properties, these groups (4A and 4B) are suggested as a destination for pyrite concentration and application in pyrite roasting (Gomes et al., 2022) and solar cells (Kristmann et al., 2022) and sulfate fertilizers.

3.3.1. Policy implications

Along with the previously discussed technical and feasibility aspects, this topic also highlights the policy implications of waste valorization. The application proposals for CMW outlined in this work align with global and local public policies.

The United Nations (UN) approved the 2030 Agenda in 2015, which included a set of sustainable development goals (SDGs) for 2015–2030. There are 17 SDGs, 169 targets, and 232 indicators covering environmental, social, economic, and institutional dimensions (Kronemberger, 2019). According to the UN, coal mining should contribute to better achievement of the SDGs through actions based on efforts focused on the circular economy.

In 2019, the Brazilian Federal Senate passed Bill No. 1496 (BRASIL, 2019) amending the National Policy on Solid Waste (BRASIL, 2010) which requires companies to allocate a portion of mining waste to manufacture construction materials beginning the fifth year after the law's publication. At the beginning of 2022, the Presidency of the Brazil Republic sanctioned law n° 14.299 (BRASIL, 2022), which proposed a fair energy transition for the Santa Catarina coal region. The law calls for developing an appropriate energy transition plan (ETP) that balances carbon emission reduction goals with socioeconomic implications and the valorization of mineral and energy resources. The ETP also outlines the operation of the coal thermoelectric plant Jorge Lacerda (located in the study region) until 2040, beginning with establishing a council for planning activities to minimize the environmental, economic, and social repercussions in Santa Catarina's southern region.

The ETP will be defined by a council of government leaders, employees, and businesses. The program aims to prepare Santa Catarina for the probable closure, until 2040, of the coal thermoelectric generation activity. This company group must look for resources to develop activities to compensate for the closure of coal mines and the repositioning of economic activities. It may also investigate technological advancements allowing it to use the region's coal for other uses, or it may continue to employ coal-fired thermoelectric generating but with zero carbon emissions after 2050.

During COP 29 (UN Conference on Climate Change), held in Baku,

Azerbaijan, in 2024, it was mentioned that the implications of a sudden change in the climate could compromise the economy through climate disasters. The participation of academia, research, development, and educational institutions in creating favorable environments to transform plans into action was also highlighted. Initiatives such as Brazil's for the just energy transition (ETP) align with the issues discussed at the conference. Regarding the need for cheap and clean energy, the use of fossil fuels must be gradually reduced, and the technological development for this transition can be the basis of economies around the world (UN, 2024).

4. Final considerations

This study utilized an innovative sampling strategy in the extreme south of Santa Catarina, collecting waste from various stages of coal processing across multiple mining companies. Unlike traditional methods that blend residual materials for transfer to landfills, this research analyzed 24 distinct residual fractions. This approach allowed for a detailed characterization of the differences and similarities between the geological sources of coal and the beneficiation processes employed by different companies.

The findings indicated that residual fractions from the Barro Branco layer predominantly contain kaolinitic clays, while those from the Bonito coal layer are richer in illite clays. Both layers, however, contain pyritic material mixed with the clays. The beneficiation processes influence the pyritic content of these fractions, which determine pyrite concentration.

This analysis grouped residual fractions based on shared characteristics, resulting in targeted proposals for potential applications. Group 1, which has a higher carbon content, is suitable for processing and carbon concentration. Group 2, characterized by low pyrite content, coarse granulometry, and neutral pH, can be utilized to concentrate clay minerals for ceramics and mortars. Group 3, rich in clay minerals, is appropriate for fertilizers, techno-soils, pozzolans, and geopolymers. Group 4 includes samples that show potential for pyrite concentration.

Future research will focus on validating the proposed applications for each waste fraction. This innovative approach to classifying coal waste based on geological origin and production characteristics paves the way for maximizing the use of run-of-mine (ROM) materials and promoting a more circular economy in the mining sector.

CRediT authorship contribution statement

M.N.S. Faraco: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **L. Simão:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **J. Acordi:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **E.F. Olivo:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis. **A. Zaccaron:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis. **O.R.K. Montedo:** Writing – review & editing, Visualization, Supervision, Resources, Investigation, Conceptualization. **M.J. Ribeiro:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Funding acquisition, Formal analysis. **C.P. Bergmann:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **F. Raupp-Pereira:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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