Ferns and Licophytes in Coal Mining Waste and Tailing Landfills

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Abstract

Mineral coal extraction in Santa Catarina State (Brazil) Carboniferous Basin has degraded the local ecosystem, restricting the use of its areas. One of the biggest environmental impacts in the mining areas is the uncontrolled disposal of waste and sterile mining with high concentrations of pyrite, which in the presence of air and water is oxidized promoting the formation of acid mine drainage (AMD). These contaminants can be leached into water resources, restrict the use of water, soil and cause threats to fauna and flora. This study aimed to characterize these areas as to the content of Cd, Pb, Ni and Zn metals in the tailings and waste resulting from coal mining and to survey the species of ferns and lycophytes present. Wastes and tailing samples and specimens of ferns and lycophytes were collected in 23 landfills in six municipalities in the region and in four underlying areas used as controls. Chemical and physical analyses (pH in water and pH in KCl, Ca, Mg, P, K, Na, Mn, Fe, Al, clay and OM contents) were carried out and the total contents of heavy metals Cd, Pb were determined, Ni and Zn. Sampling of ferns and lycophytes was carried out by walking. The levels of heavy metals, Cd, Ni and Zn were below the prevention concentrations established by CONAMA Resolution 420/2009. Pb levels were above prevention values in four landfills. Sixteen species of ferns and one lycophyte were found, with hemicryptophytes the most frequent and helophytes the most adapted to the environment. Of the species found, *Pteridium esculentum* (G. Forst.) Cockayne, *Pityrogramma calomelanos* (L.) Link and *Telmatoblechnum serrulatum* (Rich.) Perrie, DJ Ohlsen & Brownsey demonstrated resistance to degraded and contaminated environments with Pb, which may constitute an alternative for projects monitoring and environmental recovery.

1 Intruduction

Coal mining activity brought economic and social development to the southern region of Santa Catarina State, allowing the emergence of other sectors such as the ceramic, plastic and chemical industry. However, the activities of extraction, processing, transportation and storage of tailings and mining waste, over the years, have resulted in the contamination of natural resources and deforestation (Souza Junior et al. 2018).

For each ton of coal mined, about 60% of solid waste (tailings and waste) is generated (Campos et al. 2010). The term tailing means tailing pyrite, mine tailings and coal waste. These materials rich in iron sulphide (pyrite - FeS_2), when in contact with water and atmospheric air, undergo oxidation reactions forming acidic chemical compounds, susceptible to leaching, responsible for the acid mine drainage (AMD) process, the main environmental impact in mined areas (Bilibio et al. 2020).

AMD is characterized by low pH (≤ 3), presence of Al, Fe, Mn and trace elements As, Cd, Cu, Ni, Pb, Zn, Cr and Hg in compositions and concentrations that depend on the kinetics of geochemical processes, mineralogy, type and quantity of oxidized sulphide, temperature, bacteria action, among other factors specific to each environment, which condition contamination levels, and can remain active for decades and even centuries after its production (Cunha et al. 2019; Yuan et al. 2019).

Although tailings and waste landfills are complex environments to support life, there are plant species capable of surviving in these places, such as some of pteridophytes, which are resistant to degraded environments, as they are undemanding in soil fertility, survive for long periods of drought and withstand environmental adversities well. These species cause the natural regeneration process to occur, once they begin colonization, creating conditions for other species to settle (Eslava-Silva et al. 2019; Marques and Krupek 2019; Praveen and Pandey 2020).

Due to the fact that they can survive in inhospitable places such as tailings landfills, have rusticity and are native species of the region, some pteridophytes can be a form of initial recovery of areas impacted by mining, seeking to re-establish ecological structures and functions that existed in the ecosystem before degradation (Prabhu et al. 2016). Pteridophytes include phytoremediation species capable of phyto volatizing, phyto stabilizing and phytoextracting heavy metals (Praveen and Pandey 2020).

The knowledge of the species of ferns and lycophytes capable of inhabiting the tailings and tailing landfills of mining is of importance, because in addition to the rusticity, some species are native to the region and can integrate projects of environmental recovery promoting the restructuring of the local ecosystem. In order to find viable alternatives for the restoration of ecosystems degraded by coal mining, this study presents a survey of pteridophytes that occur naturally in areas of tailings landfills in the Santa Catarina carboniferous basin and their relationship with high levels of heavy metals.

2 Materials And Methods

A study was carried out in 23 landfills and dumps of pyrite waste and in four areas without mining interference, in six municipalities belonging to the Santa Catarina state Carboniferous Basin, which occupies an area of 1,659 km^2 (Milioli et al. 2009).

Sample points distribution on landfills was made according to the availability of entry into the areas, and in the cities of Criciúma and Urussanga, five landfills were according to the availability of entry into the areas, and in the cities of Criciúma and Urussanga, five landfills were collected each, in Lauro Muller and Siderópolis in four landfills each, in Treviso in three landfills and in Forquilhinha in two landfills. Areas without mining interference are located in Siderópolis (1) and Urussanga (3) (Figure 1). Details on the study areas are shown in Table 1.

Table 1 - Description of study areas where coal mining tailings landfills are located in southern Santa Catarina.

Municipality	Area	Estimated age (years)	Area ID (*)	Description
Urussanga	**A1**	32	Setor Santana Ravine area 3	Two environments: (1st) Landfill of coal fines and ultrafines; (2nd) landfill of waste.
A2	32	Roadside ravine	Tailings landfill	
A3	32	Setor Santana Plano II area 4	Fine and ultrafine coal Landfill	
A4	32	Setor Santana Well 8 area 1	Tailings landfill	
A15	32	Open area	Open pit mining. Absence of topography and soil construction practices. Presence of tailings and waste.	
AT2	-	Control	Roadside ravine	
AT3	-	Control	Roadside ravine	
AT4	-	Control	Roadside ravine	
Treviso	**A6**	52	Open area	Open pit mining. Two environments: (1st) Absence of topography and soil construction practices. Tailing landfill. (2nd) Landfill of fine and ultrafine coal.
A20	52	Area União	Tailings landfill	
A21	52	Area União	Landfill of pyrite waste, mixture of soil and rock fragments.	
Siderópolis	**A7**	42	Língua do Dragão	Thin and ultrafine landfill. It currently receives effluents from other ditches located around it.
A19	42	Open area	Open pit mining. Absence of topography and soil construction practices. Presence of tailings.	
A22	42	Mina do Trevo	Open pit mining with the presence of a small layer of “soil” on the surface covering tailings-pyrite.	
A23	42	Mina do Trevo	Open pit mining with the presence of a small layer of "soil" on the surface covering tailings - pyrite.	
AT1	-	Control	Roadside ravine	
Criciúma	**A8**	42	Bairro Colonial	Tailings landfill
A9	42	Bairro Santa Luzia	Tailings landfill. Urban solid waste deposition.	
A16	42	Setor Linha Batista	Two environments: (1st) Landfill of waste. (2nd) Landfill of fine and ultrafine coal. Occurrence of solid urban waste.	
A17	42	Setor Linha Batista	Two environments: (1st) Landfill of waste. (2nd) Landfill of fine and ultrafine coal. Occurrence of solid urban waste.	
A18	42	Setor Linha Batista	Tailings landfill. Presence of AMD, rock fragment and pyrite; intermittent lake formed by the contribution of precipitation with bluish water.	
Forquilhinha	**A10**	52	Landfill	Deposition of fine and ultrafine coal.
A11	52	Landfill	Decanting basin of fine and ultrafine coal with the presence of small ponds with reddish water and occurrence of AMD on de banks.	
Lauro Muller	**A5**	40	Rocinha	Pyrite waste landfill
A12	40	Area 10	Tailings landfill	
A13	40	Area 4	Tailings landfill	
A14	40	Open area	Tailings landfill	

*Areas identification according to the Federal Public Ministry of Santa Catarina official nomenclature.

Geology of the region falls within the Guatá Group, which includes non-glacial sediments and layers of coal, constituting the Rio Bonito (lower) and Palermo (upper) formations. The mineralogical constitution of Santa Catarina coal has quartz, kaolinite, plaster, muscovite, K-feldspar, as well as ferrous (sulphides), iron oxides and Al hydroxide silicates (Flores 2018). The representative soils of the region are Ultisols (43.1%) and Inceptisols (24.2%) (Milioli et al. 2009).

2.1 Sample collection and evaluation methods

The collections of fern and lycophyte specimens, pyritic waste and soil surrounding each plant were carried out using the walking method suggested by Filgueiras et al. (1994).

All plants were carefully removed completely and packaged, preserving the characteristics of each individual, as well as the pyrites and the soil. Samples of specimens and tailings were taken to the UDESC/CAV Environmental Survey and Analysis Laboratory for processing. Plants received identification, by delimiting families, following the classification proposed by Pteridophyta Philogeny Group (PPG I 2016), with genera and species being updated their scientific names by Flora do Brasil under construction (2020). For most species, the most relevant synonym was placed in the table with the floristic list, due to the fact that ancient scientific names are still found in some consulted bibliographies. Collected plants were desiccated, catalogued and incorporated into the collections of the LUSC Herbarium of the State University of Santa Catarina (UDESC/CAV) and the CRI Herbarium of the University of the Far South of Santa Catarina (UNESC).

The pyritic waste and the soil were dried in an oven for 24 h at 60 ºC, being ground and passed through a 2 mm sieve. To characterize the tailings and soil, pH in water was determined using a soil/solution ratio of 1: 1, contents of P, K and Na by the Mehlich method; Ca, Mg and Al with KCl 1 mol L^{-1} solution (Tedesco et al. 1995) and organic matter (Walkley and Black 1934). Quantification of the Ca and Mg content was performed in an atomic absorption spectrometer, P and MO in UV-visible, and K by flame photometry. The determination of clay contents was based on the methodology proposed by Day (1965) and Gee and Bauder (1986). The pH values in KCl were also determined (EMBRAPA 1997).

Subsequently, in the tailings and soil samples, the total contents of Cd, Pb, Ni and Zn were determined, following the USEPA protocol, method 3051 (USEPA 2007). All analyses were performed in duplicates. The reliability of the analytical method was assessed using reference soil samples certified by the National Institute of Standards and Technology (NIST). For the analyses in question, the soil sample SRM 2709 A (San Joaquin) was used as reference. The Qualitative detection limit (QDL) was also determined (Table 2).

The quantification of the total contents of Pb, Ni and Zn took place by means of the atomic absorption spectrometer, with atomization in CONTRAA 700® air-acetylene flame (ANALYTIK JENA) and the total contents of Cd by the same equipment, however with electrothermal atomization, using as a chemical modifier the use of 1g of $NH_4H_2PO_4$ in 0.5 mol L^{-1} HNO_3 (Rucandio and Petit 1999).

Table 2 - Certified and recovered values of the trace elements of the reference sample NIST SEM 2709 A (San Joaquin) and Limit of operational detection and quantification, QDL respectively.

Element	**NIST SEM 2709 certified**	**% NIST recuperation**	**QDL**
		mg kg^{-1}	mg L^{-1}
Cd	0.31 ± 0.002	109.90	0.2113
Pb	29 ± 0.1	95.37	0.0718
Ni	85 ± 2	79.45	0.0377
Zn	103 ± 4	85.90	0.0093

2.2 Statistical analysis

Statistical analysis was conducted in three phases. Initially, data were submitted to descriptive analysis, aiming to characterize the frequency distributions of the variables and to identify outliers. Next, a univariate analysis of variance was performed for the effect of the area factor on the variables Cd, Pb, Ni and Zn followed by the Scott-Knott test, when relevant. The grouping analysis of the areas was also carried out according to the presence or absence of the observed species. In the tests, the minimum significance level of 5% was adopted. The determination of the multivariate distance between the areas was performed based on the presence or absence of pteridophyte species from the Jaccard index calculation. Ward's hierarchical method was adopted as an agglomeration algorithm (R Core Team 2019).

3 Result And Discussion

31. Chemical, physical and heavy metal characterization of waste and tailing

Tailings and waste resulting from coal mining have low values of pH, clay and sum of bases as well as low levels of Ca, Mg, K, Na and Mn and high levels of P, Al, exchangeable Fe and organic matter. Of the 23 landfills evaluated, only A23 has different chemical properties, with high values of pH, Ca, Mg, SB, P, Mn and organic matter and low Al levels when compared to the other landfills (Table 3). The low pH values are due to the presence of sulphidized minerals such as pyrite (FeS_2), contained in the tailings and tailing landfills, which oxidize giving rise to AMD, producing sulfuric acid and causing the pH to fall (Staub 2019).

Table 3 - Characterization of waste pyrite and tailing from coal mining in the 23 landfills and soil in the 04 areas without mining interference, in the Santa Catarina Carboniferous Basin. Values average (*).

LF	pH water	pH KCl	Ca	Mg	K	Na	SB	Al	P	M.O	Ar.
Cmolc kg^{-1}	mg kg^{-1}	g kg^{-1}									
A1	2.8	2.8	3.2	0.1	1.0	0.1	4.5	7.3	3.3	56	180
A2	3.2	2.6	3.7	0.2	0.2	0.1	4.2	4.6	1.5	54	190
A3	3.0	2.7	6.3	0.1	0.1	0.1	6.7	7.3	2.1	46	140
A4	2.6	2.1	4.4	0.1	0.1	0.1	4.6	5.8	1.2	36	150
A5	2.7	2.5	5.7	0.1	0.1	0.1	6.0	7.0	3.2	56	150
A6	2.6	2.7	4.0	0.1	0.1	0.2	4.3	7.9	2.1	40	180
A7	2.5	2.4	3.6	0.1	0.1	0.1	3.9	5.2	2.7	93	190
A8	3.2	3.0	4.7	0.1	0.1	0.2	5.0	5.3	1.5	37	340
A9	2.2	2.4	3.2	0.1	0.1	0.1	3.5	9.7	2.5	93	400
A10	2.8	2.9	6.3	0.3	0.4	0.3	7.3	9.1	21.4	61	240
A11	3.0	2.8	4.9	0.1	0.1	0.2	5.3	8.0	1.9	24	240
A12	3.0	2.8	3.7	0.2	0.1	0.1	4.1	9.5	2.7	30	180
A13	3.3	2.8	2.7	0.1	0.2	0.1	3.1	7.6	1.6	39	240
A14	3.1	2.7	4.0	0.1	0.1	0.2	4.5	4.9	10.0	31	225
A15	3.0	2.9	2.4	0.1	0.1	0.2	2.7	6.4	8.0	18	220
A16	2.8	2.9	5.3	0.1	0.1	0.2	5.7	10.2	2.6	24	220
A17	3.4	3.2	3.5	0.1	0.3	0.2	4.3	7.7	23.8	18	270
A18	3.1	3.0	3.5	0.1	0.2	0.1	4.0	6.7	1.45	29	190
A19	3.2	2.9	3.3	0.1	0.2	0.1	3.7	7.8	1.0	36	240
A20	3.3	3.3	3.8	0.1	0.2	0.2	4.3	11.3	2.3	15	300
A21	3.0	2.7	3.9	0.1	0.2	0.2	4.5	6.9	6.3	18	200
A22	2.8	2.7	3.1	0.1	0.1	0.2	3.2	4.1	12.4	26	220
A23	5.3	5.5	33.4	3.0	0.1	0.2	36.8	1.9	81.9	44	220
AT1	4.2	5.8	6.9	0.1	0.3	0.3	7.6	4.1	3.6	21	380
AT2	4.3	3.9	4.5	0.1	0.2	0.2	5.0	1.5	2.3	18	190
AT3	4.0	3.5	4.3	0.1	0.3	0.2	4.9	7.2	3.2	17	290
AT4	4.1	3.6	4.5	0.1	0.2	0.2	5.0	4.0	3.3	16	220

(*) LF: Landfill; A: Landfill area; AT: area without mining interference. Med: Average; Min.: Minimum; Max.: Maximum.

Low levels of Ca, Mg, K, Na and Mn that result in low base sum values, denote the loss of the elements by leaching. This occurs due to the weathering of the minerals contained in the tailings, caused by AMD, which releases substantial loads of SO_4^{2-}, which can be associated with the elements and result in the loss by leaching (Kefeni et al. 2017). High levels of P, can be attributed to the formation of iron and aluminium oxides and hydroxides by the acid drainage process, leading to the specific adsorption of the element (Boukemara et al., 2017).

High levels of exchangeable Fe and Al are due to the presence of iron and aluminium minerals in the tailings and to the AMD process that increases the soluble forms of these elements. The free forms of Fe and Al occur only in extremely acidic conditions (pH <1), whereas complexation with metals is dominant at pH ranging between 1.0 - 4.5 for Fe and 1.5 - 6, 0 for Al (Nordstrom 2020).

Organic matter content is considered high, compared to the control areas, which can be caused by the type and origin of Santa Catarina coal and the method of determination used. Santa Catarina coal is of the sub-bituminous coal type originated from plant material, containing high amounts of organic carbon (80 to 85%) in its composition, due to the carbonification process. Estimating organic matter in mined areas is difficult due to the carbon contribution from the coal fragments and the Fe and Mn oxidation reduction processes (Somani et al. 2020).

The A23 landfill has different chemical properties, because, according to information from the National Department of Mineral Production (DNPM), it had already undergone a recovery process in 2005, in compliance with the Plan for the Recovery of Degraded Areas (PRAD). However, it was considered in this study because it still contains tailings mixed with the soil. The chemical properties related to the exchange complex, Ca, Mg, Na, K and sum of bases (SB) have values higher than those found in other landfills and similar to areas without contamination. These results agree with those obtained by Inda et al. (2010) in soils built in SC, indicating a more active process of proton dissolution of buffering minerals, possibly present in the soil used in the recovery. The higher pH and P content indicate the correction of the soil built through liming and fertilization.

Control areas showed similar chemical properties, having low levels of basic cations (Ca, Mg, K and P), low pH values and high levels of exchangeable Al (Table 3), demonstrating that the soils in the region are chemically poor, with an halitic character, that is, with low base saturation and high with Al, high activity clay, exchangeable Al levels greater than 4 $cmol_c\ kg^{-1}$ (Campos et al. 2003).

Table 4 - Trace elements content in the tailings and waste from coal mining and in the soil of areas without contamination, in the Santa Catarina Carboniferous Basin (*).

Landfill/Control	Cd	Pb	Ni	Zn
mg Kg^{-1}				
A1	0.6 a	59.3c	1.6e	34.7 c
A2	0.6 a	81.2c	4.8d	41.1 c
A3	0.6 a	50.2c	4.3d	56.9 c
A4	0.6 a	43.2c	3.0d	42.0 c
A5	0.6 a	58.4c	2.6e	56.7 c
A6	< LDQ	51.6c	7.5c	49.1 c
A7	0.8 a	349.1 a	2.3e	54.5 c
A8	< LDQ	50.7c	3.7d	50.0 c
A9	< LDQ	162.4 b	2.4e	42.6 c
A10	0.3 a	43.9c	12.8 b	42.2 c
A11	0.3 a	61.8c	21.3 a	71.0 b
A12	0.6 a	31.0c	5.1c	35.7 c
A13	< LDQ	34.6c	8.4c	46.9 c
A14	< LQO	45.4c	7.2c	34.3 c
A15	0.6 a	64.4c	4.9c	35.7 c
A16	0.6 a	58.2c	2.1e	84.2 b
A17	0.6 a	29.8c	9.6b	43.1 c
A18	0.6 a	73.9c	7.2c	178.0 a
A19	< LDQ	47.0c	6.2c	83.2 b
A20	0.6 a	40.7c	9.9b	57.0c
A21	0.6 a	38.6c	10.7 b	35.7 c
A22	< LDQ	62.9c	3.4d	60.4 c
A23	< LDQ	34.6c	9.8b	88.7 b
AT1	< LDQ	64.2c	5.4c	77.7 b
AT2	< LDQ	48.2c	2.5e	68.5 b
AT3	0.4 a	51.2c	1.6e	80.2 b
AT4	< LDQ	68.9c	5.9c	50.4 c

(*) Averages followed by the same letters in the vertical do not differ by the Scott-Knott test (P > 0,05); LDQ = 0,2113.

Total levels of trace elements Cd, Pb, Ni and Zn quantified in the tailings can be seen in Table 4. No differences were observed in total levels of Cd between the studied sites, with most of them being below the detection limit instrumental. The Ni content provided the greatest discrimination between the locations, separating them into five distinct classes, only six landfills presented values higher than the control areas. In the case of Zn, three classes were formed, with only the A18 landfill (178 mg kg^{-1}) having a higher concentration than the control areas. These two elements, together with the Cd, presented levels below the prevention values established by Resolution 420/2009 of Conama (30 mg kg^{-1}, 300 mg kg^{-1} and 1.3 mg kg^{-1}, respectively) (Brazil 2009).

The Pb contents observed in landfills A7, A9, A2 and A18, were higher than the prevention value (72 mg kg^{-1}), established by CONAMA Resolution 420/2009 (Brazil 2009). The presence of these elements may be associated with metal sulphides that have a high affinity for trace elements, as well as pyrite that can naturally adsorb them on its surface (Tabelin et al. 2020). There is a direct influence of pyrite on the concentrations of all toxic elements of the tailings including sulphur, reporting it as an omnipresent component with environmental relevance, considering it as a reservoir of trace elements (Dutta et al., 2020).

Some other factors such as the geochemistry of heavy metals and the time of formation and exposure of landfills (Table 1) may be associated with the concentration of these elements. The concentration of heavy metals in the tailings and waste is also conditioned to the mineralogical composition of the coal that brings with it different metallic ions. Brazilian coal is characterized by a high range of sulphide minerals such as pyrite, marcasite and secondary minerals, formed from the AMD process, such as jarosite and schwertmannite, which can assimilate elements such as Pb, As and Cr (Oliveira et al. 2019; Mireles et al. 2016). The oxidation of other iron sulphides, such as pyrrhotite (FeS), arsenopyrite (AsFeS) and chalcopyrite ($CuFeS_2$), can also generate acidic solutions and provide toxic elements. However, not all sulphide minerals present in mineral coal undergo acid hydrolysis, galena (PbS), sphalerite (ZnS) and chalcocite (CuS), for example, can release metals present in their structures without causing acidity which depends on the chemical balance of the medium (Benavente et al. 2020). Thus, the occurrence of Cd, Ni, Zn and Pb, in the coal tailings, even in amounts considered low, is indicative of the dissolution of potentially contaminating minerals.

Under low pH conditions Cd, Ni and Zn form electrostatic bonds with clay minerals and organic matter, with their exchangeable and soluble forms favoured which can cause losses by leaching (Duarte et al. 2019). Evaluating the leachate from the coal residue of SC, Silva et al. (2011) found Mn, Zn, Cu, Co and Ni as the main elements leached under low pH conditions, whereas Cd and Zn were found at higher levels than the average of the world's coals, occurring mainly in pyrite and alternatively in some clay minerals. According to the studies by Cutruneo et al. (2014), the oxidation of sulphides in coal waste from Santa Catarina, showed high concentrations of Zn, Cu, Mn, Co, Ni and Cd in the leachate, associated with acidic conditions and the oxidation of pyrite, these elements being lost in a short time.

The high levels of Pb occurring in landfills A2, A7, A9 and A18, may be associated with the geochemistry of the element, which is not very mobile and may be complexed by organic matter, chemosorbed in silicate oxides and minerals and precipitated as carbonate, hydroxides or phosphate, being one of the most abundant toxic metals in coal (Pelletier et al. 2020). Most of the Pb can be adsorbed by goethite. Its stability field in the Pb-S-C-O-H system is small, mainly at low pH values (pH <5) combined with oxidation conditions and high concentrations of sulphates in solution (Akopyan et al. 2018).

Lead can bioaccumulate in the food chain and is a metal that has no beneficial nutritional effects known to animals. Despite the low mobility, when it comes into contact with chelating agents, it can be solubilized in the soil and be absorbed in greater quantity by plants (Babaeian et al. 2015). In the human body, lead can cause neurotoxic, haematological, cardiovascular, gastrointestinal effects, kidney disorders, arterial hypertension and has evidence of carcinogenicity (Ruppenthal 2013; Grant 2020). Studies demonstrate a strong relationship between exposure to lead and cadmium and functional dependence in an elderly population (Chen et al. 2020; Hara et al. 2016; Musilova et al. 2016).

3.2 Ferns and Lycophytes

17 species were registered, distributed in 14 genera belonging to 11 botanical families of pteridophytes in the areas of tailings landfills and mining waste in the region of the Santa Catarina carboniferous basin (Table 5).

Table 5 - Species of ferns and lycophytes found in the tailings and waste landfills of mining in the region of the Santa Catarina carboniferous basin.

Family/Genus/Species/ Species code	Preferred environments *	Biological forms *	Environmental adaptations *	Place of collection (Landfills)
LYCOPHYTS				
LYCOPODIACEAE				
Palhinhæa cernua (L.) Franco & Vasc. (sin. *Lycopodiumcernuum* L.; *Lycopodiellacernua* (L.) Pic. Serm.) (**E1**)	LU, LA	C	ME, HE	A13, A14 (Lauro Muller), A15 (Urussanga), A16, A17 (Criciúma), A19 (Siderópolis)
FERNS				
ANEMIACEAE				
Anemia phyllitidis (L.) Sw. (sin. *Anemia candidoi* Brade) (**E2**)	IM, BM, BR	H	ES	A23 (Siderópolis)
BLECHNACEAE				
Neoblechnum brasiliense (Desv.) Gasper & V.A.O. Dittrich (*sin. Blechnum brasiliense* Desv.) (**E3**)	BM, IM, LA	C	ME, ES	A2, AT3 (Urussanga), A17 (Criciúma), A19, A22, A23, AT1 (Siderópolis)
Telmatoblechnum serrulatum (Rich.) Perrie, D.J. Ohlsen & Brownsey (sin. *Blechnum serrulatum* Rich.) (**E4**)	BM, IM, LA	C	ME, ES	A3 (Urussanga), A5 (Lauro Muller), A7(Siderópolis), A8, A16 (Criciúma), A22 (Siderópolis)
CYATHEACEAE				
Cyathea atrovirens (Langsd. & Fisch.) Domin (sin. *Alsophila atrovirens* (Langsd. & Fisch.) C.Presl) **(E5)**	BM	F	HE	A13, A14 (Lauro Muller), A17 (Criciúma), A19 (Siderópolis)
Cyathea cf. *phalerata* Mart. (sin. *Alsophila phalerata* (Mart.) Mart.) **(E6)**	IM	F	HE	A19 (Siderópolis)

Tabela 5 - Species found in the tailings and waste landfills in the region of the Santa Catarina coal basin (continued).

Family/Genus/Species/ Species code	Preferred environments	Biological forms	Environmental adaptations *	Place of collection (Landfills)
DENNSTAEDTIACEAE				
Pteridium esculentum (G. Forst.) Cockayne (sin. *Pteridium arachnoideum* (Kaulf.) Maxon) (**E7**)	LA, CL	H	HE	A1, A2, A3, A4, A15, AT2 (Urussanga), A6, A20, A21 (Treviso), A8, A9, A16, A17, A18 (Criciúma), A10, A11 (Forquilhinha), A5, A12, A13, A14 (Lauro Muller), A7, A19, A22 (Siderópolis)
DICKSONIACEAE				
Lophosoria quadripinnata (J.F.Gmel.) C.Chr.(sin. *Alsophila pruinata* Kaulf.) **(E9)**	BM	H	ME, ES	A19 (Siderópolis)
DRYOPTERIDACEAE				
Elaphoglossum sp. (**E8**)	LA	H	ME, ES	AT3 (Urussanga), A23, AT1 (Siderópolis)
Rumohra adiantiformis (G.Forst.) Ching (**E10**)	LA	H	ME	AT3 (Urussanga), A23, AT1 (Siderópolis)
GLEICHENIACEAE				
Dicranopteris flexuosa (Schrad.) Underw. (sin. *Mertensia flexuosa* Schrad.; *Gleichenia flexuosa* (Schrad.) Mett.) (**E11**)	LA, BR	G	ME	A12 (Lauro Muller), A17, A18 (Criciúma), A19 (Siderópolis)
Gleichenella pectinata (Willd.) Ching (sin. *Mertensia pectinata* Willd.; *Dicranopteris pectinata* (Willd.) Underw.; *Gleichenia pectinata* (Willd) C. Presl) (**E12**)	LA, BR	G	ME	A3, A15, AT2, AT4 (Urussanga), A6 (Treviso), A12, A13, A14 (Lauro Muller), A19 (Siderópolis)
NEPHROLEPIDACEAE				
Nephrolepis cordifolia (L.) *C.* Presl (sin. *Polypodium cordifolium* L.) (**E13**)	IM, BM	H	HE	A23 (Sid

Tabela 5 - Species found in the tailings and waste landfills in the region of the Santa Catarina coal basin (continued).

Family/Genus/Species/ Species code	Preferred environments	Biological forms	Environmental adaptations *	Place of collection (Landfills)
PTERIDACEAE				
Pityrogramma calomelanos (L.) Link. (sin. *Gymnogramma calomelanos* L.) (**E15**)	CL, LU, LA	H	ME, HE	A1, A2, A4, A15, AT2, AT4 (Urussanga), A5 (Lauro Muller), A6, A20, A21 (Treviso), A8, A9, A16, A17, A18 (Criciúma), A10, A11 (Forquilhinha), A12, A13, A14 (Lauro Muller), A7, A19, A22 (Siderópolis)
THELYPTERIDACEAE				
Macrothelypteris torresiana (Gaudich.) Ching (sin. *Polystichum torresianum* Gaudich.) (**E16**)	IM, BM	H	ES	A22, A23 (Siderópolis)
Christella dentata (Forssk.) Brownsey & Jermy (sin. *Thelypteris dentata* (Forssk.) E.P.St.John) (**E17**)	IM, BM	H	HE	A23 (Siderópolis)

(*) - - CL - Clearing; BM - Forest edge; BR - Ravine; IM - Inside the forest; LU - Wet Location; LA - Open Site; C - Caméfita; H - Hemicryptophyte; G - Geophyte; F - Phanerophyte; ME - Mesophyte; ES - Sciófita; HE - Heliophyte; HI - Hygrophyte; XE - Xerophyte.

Regarding the representativeness of the families, Dryopteridaceae showed the highest specific richness with three species, followed by Blechnaceae, Cyatheaceae, Gleicheniaceae and Thelypteridaceae with two species each and Anemiaceae, Dennstaedtiaceae, Dicksoniaceae, Lycopodiaceae and Pteridaceae with only one species each. Some families have certain striking characteristics, as in the case of Gleicheniaceae, Dennstaedtiaceae and Lycopodiaceae, in which their species were found exclusively in places that denote environments with direct incidence of sunlight and humidity, showing that such species develop in altered and sunny environments. The same behaviour was registered in work carried out in the Itajaí National Park, for these families (Gasper and Sevegnani 2010).

Regarding preferential environments, the predominant form was an open place comprising ten species, with greater representation in the genera *Blechnum, Elaphoglossum, Pteridium, Rumohra, Dicranopteris, Gleichenella, Palhinhaea* and *Pityrogramma*. In the interior and edge of the forest, the second largest representation was found, with eight genera, *Anemia, Blechnum, Cyathea, Nephrolepis, Lophosoria, Macrothelypteris* and *Christella*. The third preferred environment was a bank with four species of the genera *Anemia, Dicranopteris, Gleichenella* and *Lygodium*. Finally, the clearing and humid environment with only two species each, belonging to the genera *Pteridium, Palhinhaea* and *Pityrogramm*a.

Regarding biological forms, hemicryptophytes are represented by ten species in Anemiaceae, Dennstaedtiaceae, Dicksoniaceae, Dryopteridaceae, Lygodiaceae, Pteridaceae and Thelypteridaceae, which is the predominant biological form. The camphite form is represented by three species of Blechnaceae and Lycopodiaceae, followed by the geophyte form with two species of the family Gleicheniaceae and the phanerophyte with two species of Cyatheaceae. Hemicryptophytes are more frequent in several Brazilian and worldwide ecosystems (Barudanović et al. 2019; Guislon et al., 2016; Ukaj et al. 2019). The prevalence of hemicryptophytes may be related to the fact that they present the perennial seed at ground level or slightly below it. This characteristic provides protection to vegetative buds against desiccation, while species with less protected buds are subject to greater environmental stress. This is an ecological aspect of the species of this group that occur in Brazil, since numerous studies carried out in different regions of the country have cited hemicryptophytes as being the dominant biological form among species of pteridophytes (Mota et al. 2018; Cordeiro and Neri 2019; Bagheri et al. 2020).

Most species of pteridophytes have high ecological plasticity and the ability to adapt to hostile environments. Some of the registered species have the ability to adapt to more than one type of environment, such as, for example, *Anemia phyllitidis*, whose preferential environment is the interior and edge of the forest, in addition to the ravine (Mickel 2016). Although it is widely distributed in tropical regions, *A. phyllitidis* occurred in only area A23, where signs of recovery were observed, being located at the edges and interior of spontaneous vegetation; the species is an herbaceous with terrestrial habit and preference for shaded (scyophyte) and humidity environments, this being the scenario found in the collection area. *Telmatoblechnum serrulatum* and *Neoblechnum brasiliense* occur at the edge and interior of the forest and open area, *Nephrolepis cordifolia, Macrothelypteris torresiana* and *Christella dentata* in the interior and edge of the forest, *Pteridium esculentum* in open and clearing, *Dicranopteris flexuosa*, *Gleichenella pustinata* and *Lygodium venus* and gully and *Pityrogramma calomelanos* in clearing, humid and open place (Pena et al. 2019).

Rumohra antecediformis, despite having the sciophyte form as an environmental adaptation, is common in altered environments, such as the ones in the present study, being able to develop in places with constant solar incidence and varied water supply. *Lygodium venustum*, adapted to humid environments, mesophilic form, was found in numerous collection areas, having as a common characteristic the substrate formed by pyrite and visibly humid tailings (Bauret et al. 2017).

As for exotic species, only *Macrothelypteris torresiana* was found in the study areas. This species is naturalized in the neotropics and was introduced from the tropical and subtropical regions of Africa, Asia and the Pacific Islands. It is common in altered humid places, and can form a spore bank (Pena et al. 2019).

In relation to environmental adaptations, the most representative species were heliophytes, encompassing five families and seven species, followed by two families with one species each that contemplate two forms of adaptations: mesophyll and heliophyte. The locations where they were found contained pure pyrite and tailings mixed with rocks covering the coal layer, with sparse undergrowth, constant sunlight and little humidity, demonstrating the potential that pteridophytes have to survive inhospitable environments.

The species of Blechnaceae (*Telmatoblechnum serrulatum* and *Neoblechnum brasiliense*) and Dryopteridaceae (*Elaphoglossum sp.)* And Dicksoniaceae (*Lophosoria quadripinnata)* fall under the mesophyte and scyophyte classification and *Rumohra antecediformis*, also belonging to the Dryopteridaceae family. These plants need shady and humid environments to survive, which denotes the relevance of this group in the actions after the recovery process of areas degraded by coal mining. They were found, preferably, in older landfills, some with recovery attempts, where the substrate was formed by tailings, solum and cover rocks of the coal layer and with other pioneer and secondary plant species of angiosperms, observing that in some places also had exotic trees.

3.3 Species of ferns and lycophytes and their adaptation to environments

Figure 2 shows a multivariate analysis of the presence of fern and lycophyte species in the study areas. Areas AT3, A21, A20, A11, A10, A9, A1 and A4 landed only two species belonging to this group.

Area 19 has been used for mining for 42 years and is characterized as open pit mining with the presence of waste. This area presented the greatest diversity of species, which may be related to the absence of Cd and Pb concentrations lower than the values established by brazilian legislation.

Pteridium esculentum and *Pityrogramma calomelanos* were found in the four areas with the highest concentration of Pb (A7, A9, A2 and A18). *Neoblechnum brasiliense* was found in A2, *Telmatoblechnum serrulatum* in A7 and *Dicranopteris flexuosa* in A18. This wide distribution in the sampled areas, mainly of the aforementioned species, is probably related to the fact that many pteridophytes are normally found in a variety of environments with greater anthropic activity (Lehn et al. 2020; López et al. 2020). *Telmatoblechnum serrulatum* occurs in area A7 (349.1 mg kg^{-1} of Pb), but no scientific studies have been found on the accumulation of heavy metals for this species. However, accumulation of As has been reported to *Blechnum orientale* L. by Wang et al. (2007).

Pteridium esculentum was found in 22 areas and *Pityrogramma calomelanos* in 21 of the 23 areas. Most of these areas are characterized by being landfills of raw tailings, that is, with no recovery process applied yet, unlike the areas where there was no occurrence of these species, which, visually, had signs of recovery, as they presented soil mixed with the tailings and grasses. of varied species. They are the species that occur in area A7 (349.1 mg kg^{-1} of Pb and 08 mg kg^{-1} of Cd) that presented Pb levels (Table 2) higher than those established by CONAMA Resolution 420/2009*. P. calomelanos* was observed growing in exposed tailings and with an advanced oxidation stage or when it was mixed with the soil, in more humid places and/or with accentuated solar incidence, close to stones or other plants, in some exposed gullies and clearings direct sunlight. *P. calomelanos* was used in a study for phytoremediation in mining areas and showed a high capacity to phytostabilize copper in the root and arsenic in its aerial part (Ancheta et al. 2020). *Pteridium esculentum* showed high capacity to accumulate U and Th in a study conducted in Minas Gerais (Moura et al. 2017). As they were found in areas with high concentrations of Pb, these species (*P. esculentum*, *P. calomelanos* and *T. serrulatum*) may present phytoextraction or phytostabilization capacity of heavy metals and be used in phytoremediation processes.

As mentioned above, *Pteridium esculentum* and *Pityrogramma calomelanos* were found in almost all areas, except in areas A23, AT1 and AT3 for both species, in AT4 *P. esculentum* and A3 for *P. calomelanos*. Point A23 has eight different species, the highest pH value and a high availability of phosphorus. This area has a small layer of soil covering the tailings. It is worth mentioning that the amount of phosphorus can interfere in the variety and adaptation of plant species (Copete et al. 2019).

Preferably, ferns and lycophytes occur in environments with regular water support and shading, however some of them are able to survive in dry environments with constant sunlight. For this, they developed a series of environmental adaptations such as, for example, protection against fire, water deficit, among others, allowing their development in hostile environments (Campos et al. 2018). However, caution is needed when using plants from contaminated areas due to bioaccumulation, as some species are used by humans for consumption, such as *Blechnum orientale*, which is used in the form of tea for medicinal purposes, which can cause contamination by metals (Cu, Zn, Mn, Pb, Cd, Cr, As and Hg) and by polyaromatic hydrocarbons (HPA) (Yu et al. 2020).

4 Conclusion

In the survey of ferns and lycophytes carried out in places of tailings and waste landfills in mining areas, in the southern Santa Catarina state, 17 species belonging to 11 botanical families were registered. This data showed the capacity of fern and lycophyte species to develop in extremely degraded environments, raising the possibility that species of this group of plants can be used in the initial stages in environmental recovery programs.

The presence of the species *Pteridium esculentum*, *Pityrogramma calomelanos* and *Telmatoblechnum serrulatum* in areas with high concentrations of Pb, indicates that these species may have potential for phytoextraction and phytostabilization of heavy metals.

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All authors have consent to publish this article.

Authors Contributions

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Figures

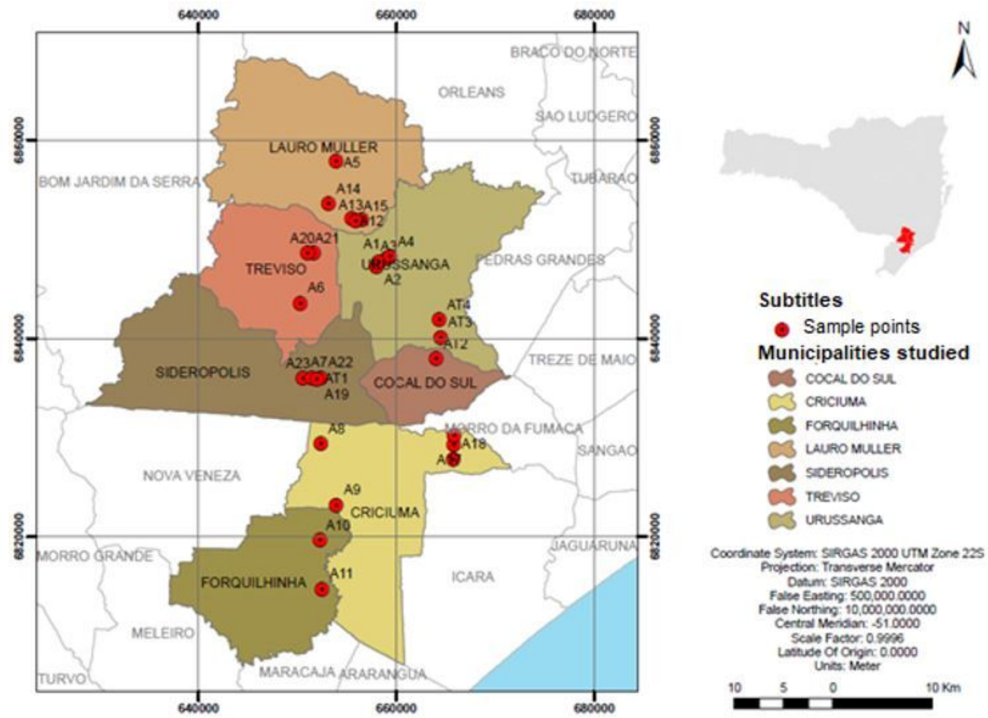

Figure 1

Location of coal mining tailings landfills in southern Santa Catarina.

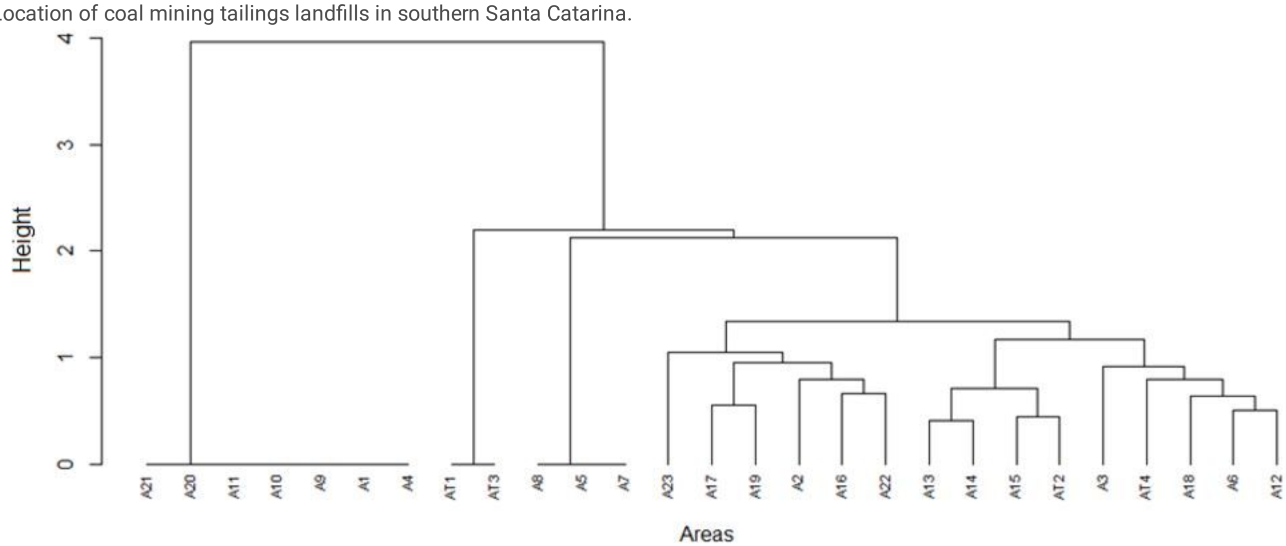

Figure 2

Multivariate distance between areas based on the presence or absence of fern and lycophyte species from the Jaccard index calculation.