Case Study of an Environmental Remediation Project Using Technosols in São Domingos Mining Area (Portugal)

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Abstract

The former São Domingos mine, located in the Iberian Pyrite Belt in southeast Portugal, is one of the country's most critical environmental legacy sites due to acid mine drainage and metal contamination. To address soil degradation, EDM – Empresa de Desenvolvimento Mineiro implemented a pilot-scale recovery strategy using engineered Technosols formulated from agro-industrial wastes. Applied over 1.5 hectares, the Technosols neutralized acidity, improved fertility, reduced metal mobility, and promoted rapid vegetation establishment. After 12 months, treated areas showed near-neutral pH, enhanced nutrient status, and stable plant cover, demonstrating that Technosols are an effective and sustainable solution for post-mining soil restoration.

Keywords: Environmental rehabilitation, acid mine drainage, degraded soils, technosols, São Domingos mine legacy site

Introduction

The São Domingos Mine, located in the Iberian Pyrite Belt in southeastern Portugal, is notable for its geological heritage and long history of mining, with periods of activity dating from the Roman period to the modern era, between 1857 and 1972 (Matos 2021). The intensive extraction of polymetallic ores, particularly copper, sulfur, and zinc, caused socioeconomic impacts and profound changes to the landscape and local ecosystems (Batista *et al*. 2003; Matos 2021).

Intense mining and metallurgical activity have resulted in extensive areas of tailings and slag deposits rich in sulfate. The oxidation of these materials, in contact with oxygen and water, generated acid mine drainage processes, characterized by the formation of hyperacidic and hyperoxidizing waters with high concentrations of potentially toxic metals and metalloids, affecting the surface water system and reservoirs constructed during the mining phase (Mendonça *et al*. 2003).

The persistence of extreme pH and redox potential conditions promote acid hydrolysis, mineral dissolution, and accelerated weathering, leading to the near-total elimination of the original soil cover. This situation, intensified by high temperatures and low precipitation, characteristics of the regional climate, favor the continuous mobilization of potentially toxic elements and delays the natural recovery of the affected systems. As a result, the soils have reduced buffering capacity, low water and nutrient retention, and limited geochemical immobilization capacity. Vegetation cover is sparse and fragmented, dominated by tolerant arbustive species such as *Cistus ladanifer L.*, reflecting an incipient stage of succession and restricted functional diversity.

Since 2001, EDM – Empresa de Desenvolvimento Mineiro, S.A., a Portuguese State-Owned Company, has been granted the responsibility for the environmental remediation of all mining legacy sites in

Portugal, under a concession contract established by the Decree-Law 198-A/2001. The environmental remediation planned for the former mining area of São Domingos covers a very large area that represents a substantial legacy of environmental, visual, and landscape changes. For this reason, these are highly complex interventions, and their implementation is expected to take place in six phases, to be carried out sequentially and in stages over time. The first two phases of the remediation, completed in 2021, consisted of recovering the existing perimeter channels for collecting runoff water, allowing clean water to be diverted from the right and left banks of the São Domingos stream valley. For the following phases, plans include the collection of various mining wastes deposits dispersed throughout the mining area and their proper concentration and technical confinement, the development of projects aimed at the collection and treatment of acid mine drainage, and the decontamination of soils in the Mosteirão stream valley, among other actions.

To address the identified challenges, associated with the remediation of soils affected by acid mine drainage, the application of Technosols emerges as a soil engineering approach aimed at the functional recover of degraded systems. Technosols are soils of technical origin that incorporate anthropogenic materials, such as waste, sludge, ashes, or other subproducts, and are designed to replicate the functions of natural soils (Aran 2017). Their development is based on adapting the proportions of its components to local conditions, in order to stimulate the biogeochemical and pedogenic processes that support medium and long term rehabilitation (Macías 2004; Macías *et al*. 2011).

In São Domingos Mine, a pilot study was conducted in 2020–2021 that included the physical-chemical and biogeochemical characterization of the treated areas, the formulation and application of Technosols adapted to conditions of extreme acidity and high metal content, and an assessment of their performance 6 and 12 months after application. The primary purpose of the formulation adopted was to mitigate the acidity associated with mine drainage, promote the geochemical stabilization of the system, and create conditions favorable to the progressive recovery of soil functions.

Characterization of the study areas

For the Technosols project, the study defined two application areas, designated as Area 1 (0.8 hectares) and Area 2 (0.7 hectares), covering a total of 1.5 hectares (Fig. 1). The difference between the two areas was related to geomorphological and hydrological conditions. The characterization of the soils to be remediated included the collection of 30 composite samples, allowing for an assessment of the current situation and the geochemical behavior of the existing elements.

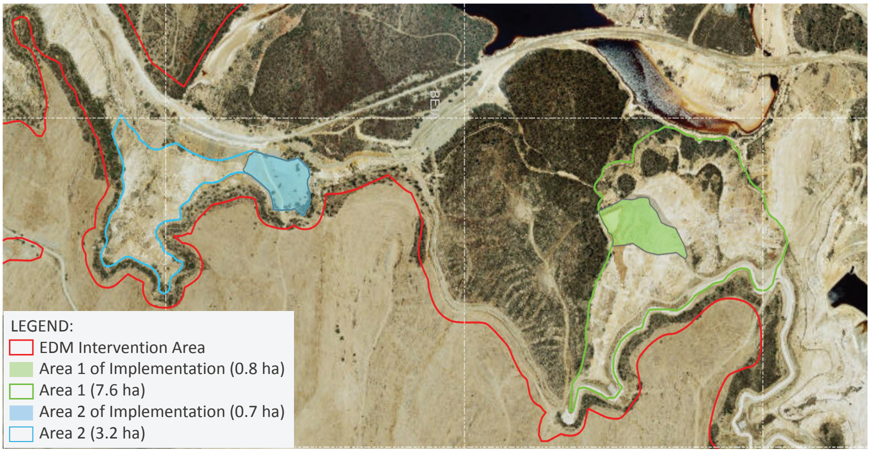

***Figure 1** Technosols implementation area. Left: Area 1; Right: Area 2.*

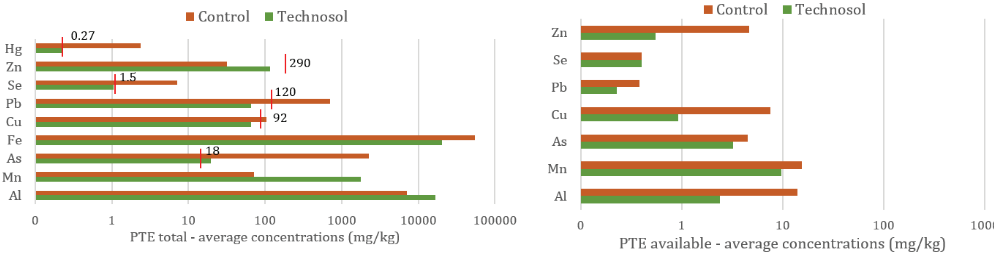

Figure 2 Average concentrations of total and available potentially toxic elements (PTE) in control and Technosol soils samples. Reference values for urban and industrial soils in environmentally sensitive areas under Portuguese legislation in right graphic bars.

In Area 1, the pH ranged from 3.15 to 5.23, with highly variable electrical conductivity (18.90–665.60 µS/cm). In Area 2, the pH was more homogeneous, ranging from 3.61 to 4.30, and electrical conductivity remained uniform, ranging from 72.70 to 307.20 µS/cm. Oxidation potentials range from 325 to 475 mV in Area 1 and from 332 to 422 mV in Area 2, indicating the presence of oxidizing conditions, characteristic of environments where the primary oxidizing agent is oxygen, and consistent with the redox values, which maintain the ferric equilibrium even in the worst materials. The C contents, both in the total and organic fractions, and N showed very low values (C < 7.5 g/kg; N < 1.5 g/kg). In terms of the particle size distribution of the fine fraction (<2 mm), the materials were classified as sandy loam.

The elements concentration in the total fraction were analyzed in terms of their toxicity to organisms and biogeochemical processes, and critical risk levels were identified for potentially toxic elements such as As, Hg, Pb, and Se. Regarding the available fraction analyzed in pore water, which allows for determining the potential risk of dispersion of potentially toxic elements through water and their effects on vegetation development, the concentrations reached levels considered critical for Al, As, Cu, Pb, and Zn (Fig. 2). The major elements were Fe (3.31–22.3%) and Al (0.33–1.99%), and the elements of nutritional interest (Ca, K, Mg, and P) had very low concentrations. Sulfate was the dominant anion.

Preparation of Technosols and application process

For the formulation of the Technosols, eight types of wastes mainly from the pulp and paper industry, provided by from *The Navigator Company S.A.*, were characterized: sand, *Dregs&Grits*, lime sludge, primary sludge, biological sludge, biomass ash, and wood scraps resulting from the combustion of residual forest biomass. In addition to these, waste from olive tree pruning in the São Domingos mine region and sludge from wastewater treatment plants were included. For the wastes with a dominant inorganic fraction, the forced oxidation kinetics were evaluated, and different responses were observed. *Dregs & Grits*, primary sludge, biological sludge, and biomass ash showed stability over time; in contrast, lime sludge and sand exhibited a rapid increase in initial pH due to the presence of alkaline solid phases, subsequently stabilizing without considerable changes. Using these residues, four types of Technosols (T1, T2, T3 and T4) were developed, each with different proportions of residues in their formulation. Technosol T1 is distinguished by its high alkalinity and buffering capacity; T2 and T3 have high cation exchange capacity; while T4 combines balanced pH, available phosphorus, and a loamy-clay-sandy texture, making it the formulation most favorable for immediate plant establishment. A total of 5,600 tons of waste was applied. The thickness of the Technosols ranged from 0.25 to 0.50 m. The premixes were received, homogenized, and subjected to a controlled maturation period. Subsequently, the Technosols were applied to experimental areas according to the defined type and thickness, followed by hydroseeding and vegetation establishment. In the control areas, the seed application rate was 10 times higher than in the pilot areas with Technosols. The vegetation plan included three vegetative levels: herbaceous, arbustive and arboreal, all consisting of native species.

In general, the applied Technosols have a neutral to slightly alkaline pH (7.2 – 8.8), a high organic C content (129±31 g/kg), N total (7.7±2.1 g/kg) and a high cation exchange capacity, with average values of 82 cmolc/kg and a complex dominated by Ca. The total fraction contains metals and metalloids that meet the regulatory limits according to Portuguese legislation, and the levels of these elements in the available fraction are very low and do not pose a risk (Fig.2). The levels of Hg in available fraction for the Technosols were below the analytical detection limit.

Monitoring and analysis of the application of Technosols

The performance of the recovery system was evaluated over a 12-month period following its application through the analysis of samples from Technosols and the soils underlying these materials, as well as from the control areas. The two control areas were established in zones adjacent to the application areas, subject to the same environmental conditions. The materials were characterized by a comprehensive range of physical-chemical and biochemical parameters, including: pH, electrical conductivity (EC), redox potential (Eh), acid neutralization capacity (ANC), total carbon, organic carbon, labile carbon, total nitrogen, and available phosphorus. Multi-elemental analyses were also performed on the total fraction and pore water. The temporal evolution of vegetation cover was assessed in both the Technosol and control areas.

Results and interpretation

The application of Technosol promoted rapid and resilient vegetation cover, with germination and regeneration occurring even after dry periods. In some locations, cover exceeded 90%, with plants showing no signs of deficiency or toxicity over time. In the control areas, cover remained very low or nonexistent, with vegetation limited to spontaneous species (Fig. 3 and Fig. 4).

Twelve months after application, the control areas maintained a hyperacidic to acidic pH, with averages of 3.98 in Area 1 and 3.95 in Area 2, associated with high redox potential levels (411 mV and 436 mV, respectively) and electric conductivity between 269 to 490 µS/cm. In contrast, the Technosols maintained an alkaline pH, with 8.05 in Area 1 and 8.33 in Area 2. The electric conductivity in the Technosols ranged from 498 to 593 µS/cm and redox potentials of 222 mV and 189 mV, favoring the stabilization of sulfate and the reduction of contaminant dispersion. The material underlying the Technosols showed improvements, with a pH close to neutrality (6.30 in Area 1 and 7.04 in Area 2), electrical conductivity ranging from 201 to 588 µS/cm, and a decrease in redox potential compared to the control areas –

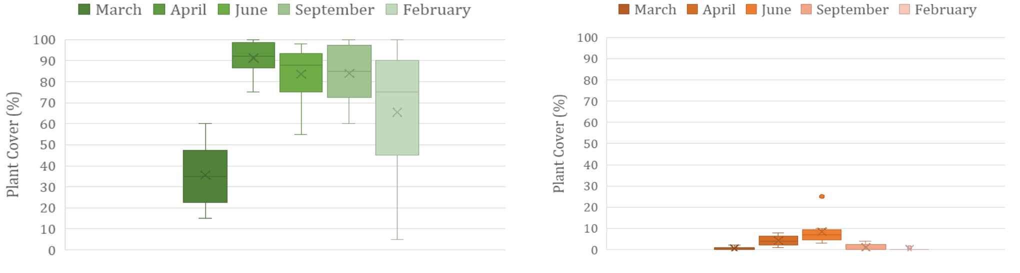

Figure 3 The evolution of vegetation cover during the different monitoring campaigns in the Technosol system (left) and the control areas (right) between 2021 and 2022.

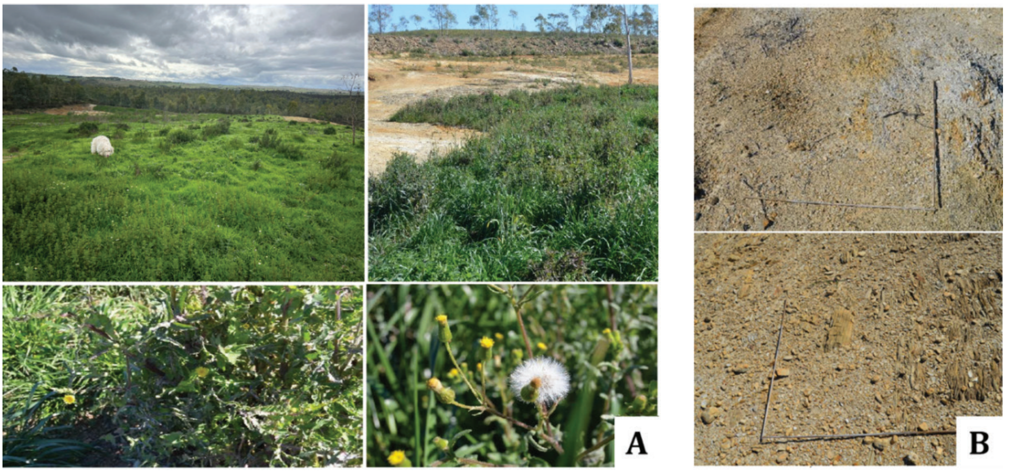

Figure 4 *State of the system's herbaceous cover. A: Area with T2 and T3 Technosols; B: Control areas 1 and 2.*

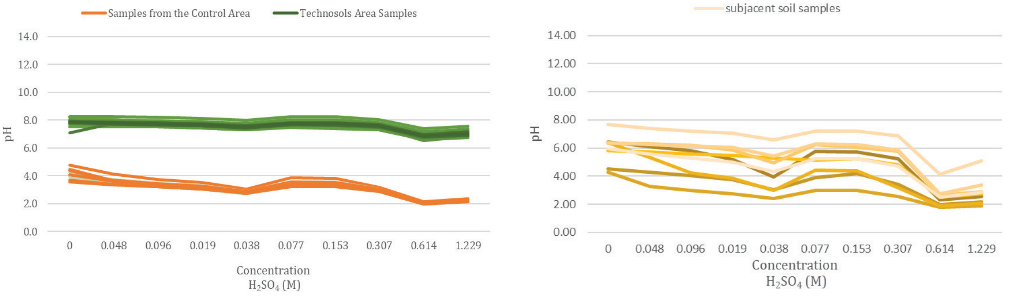

Figure 5 *Acid-Neutralizing Capacity of materials in the Control Areas and Technosols (1 and 2) (left) and subjacent soils (right).*

conditions suitable for vegetative development and promoting deeper rooting. Regarding acid neutralization capacity, the control areas remained susceptible to acidification, while the Technosols maintained high buffering potential, with a pH close to 8, even under acidic loads, functioning as an active acidity control system. In the soil samples subjacent to the Technosols, the acid-neutralizing capacity was higher than that of the control areas, demonstrating the Technosol's effectiveness in mitigating the acidification of materials at depth (Fig. 5). The carbon, nitrogen, and phosphorus contents, after 12 months, in the control areas showed low C (2.3 g/kg) and N (0.9 g/kg) contents, insufficient to sustain plant growth, with highly variable available P content (2.54 mg/kg in Area 1 and 39.52 mg/kg in Area 2). In contrast, the Technosols maintained high total C contents (74.8 g/kg in Area 1, 96% organic fraction), adequate total N (5.8–7.5 g/kg), and high available P (163.96–202.12 mg/kg), while the labile fraction of C continued to increase (10–12 g/kg). Soil samples subjacent to the Technosols showed higher values compared to the initial materials and control areas, with C concentrations 2 to 10 times higher, 50% higher N concentrations, and an increase of 10–12 mg/kg in available P concentrations, reflecting improved fertility and vegetation supporting potential.

There were reductions in the concentrations of potentially toxic elements in the available fraction analyzed in the pore water, particularly Al, Fe, As, Cu, Pb, and Sb (Fig. 6). Elements such as Cd, Se, and Cr had concentrations in the available fraction below the detection limits of the analytical methods in all samples. Although there is considerable variability in geochemical behavior, there is a clear improvement in the characteristics of these recovered soils. With regard to the concentration of elements in the total fraction of soil samples subjacent to the Technosols, increases of more than 50%, in the levels of elements important for vegetation growth, such as Ca, Mg, Na, K, and P (Fig. 7).

Future Work and Ongoing Developments

An integrated model for the management and monitoring of mining areas contaminated with potentially toxic metals is currently being developed as part of the INCOME project - *"Inputs for a More Sustainable Region: Tools for the Management of Metal-Contaminated Sites."* This model integrates biophysical characterization tools, chemical

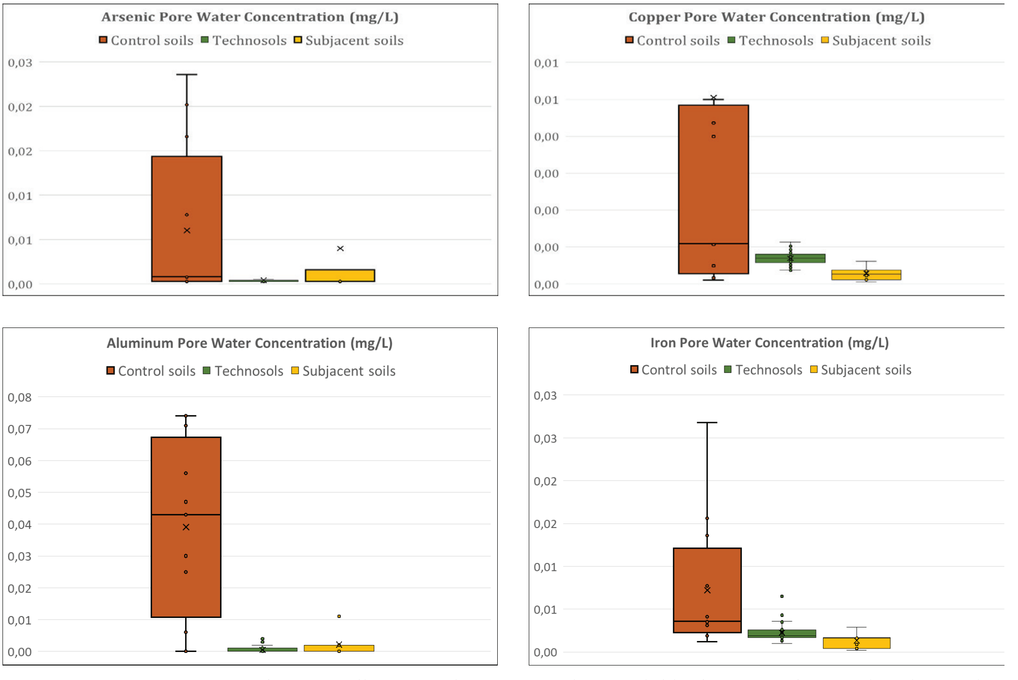

Figure 6 Concentrations of potentially toxic elements in the available fraction of control soil samples, Technosols, and subjacent soils (e.g. arsenic, copper, aluminum, iron).

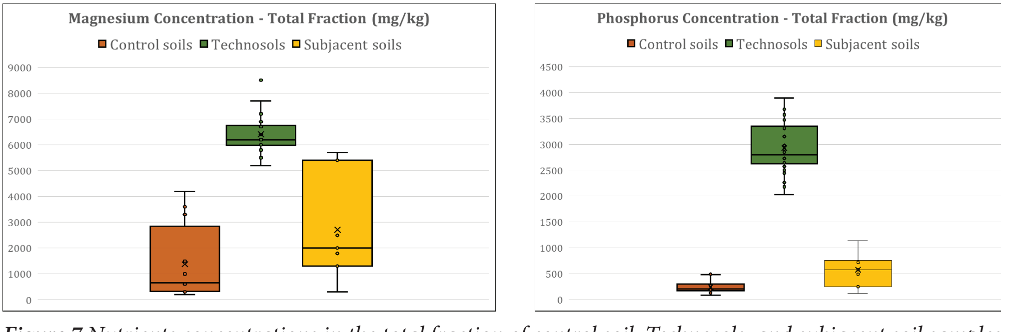

Figure 7 Nutrients concentrations in the total fraction of control soil, Technosols, and subjacent soil samples (e.g. magnesium and phosphorus).

analyses of soils and water, geophysical methods, and hyperspectral remote sensing techniques, supported by artificial intelligence algorithms. Its application will help assess degraded sites, compare their evolution with recovered areas, with and without Technosols, and support decision making, contributing to more efficient and sustainable environmental management (Oliveira *et al*. 2024).

Conclusions

In the pilot study conducted in the former mining area of São Domingos, control areas continued to pose a high environmental risk due to limited vegetation and the mobilization of potentially toxic elements, which compromised natural soil recovery. In contrast, the applied Technosols demonstrated the ability to promote rapid establishment of herbaceous cover, supported by the seed bank and spontaneous colonization, even under conditions of environmental stress. The vigorous vegetation protected the soil from erosion, promoting microbial diversity and ensuring nutrient cycling and the decomposition of organic matter. The physicochemical properties of the Technosols improved the underlying materials by limiting the upsurge of contaminant solutions, preventing salt crystallization, and stabilizing potentially toxic elements. The formulation also neutralizes acidification, increases buffering capacity, improves water and nutrient retention and promotes ecological diversity, creating favorable conditions for soil regeneration and carbon sequestration. These results demonstrate that Technosols constitute an effective strategy for mitigating environmental impacts, restoring the physical stability, chemical fertility, and biological biodiversity of the soil, and ensuring the resilience and sustainability of the ecosystems.

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