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Integrated Cartographic Inventory of Solid Mining Wastes to Support Environmental Rehabilitation: The São Domingos Mine (Portugal)

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Abstract

Historical mining districts contain heterogeneous waste accumulations whose spatial distribution and characteristics complicate environmental assessment and rehabilitation planning. This study develops an integrated, unit-based methodology for the cartographic inventory and environmental characterization of solid mine wastes, using the historical São Domingos Mine in the Portuguese Iberian Pyrite Belt as a case study. The workflow combines remote sensing, UAV imagery, terrain data, field verification, targeted laboratory analyses, and GIS, with individual waste accumulations as the basic spatial units. The methodology identified 40 waste units, comprising 23 waste dumps and 17 landfill deposits, covering 148.34 ha and classified into seven waste categories. Industrial residues, volcanic rock-derived wastes, and schist-dominated wastes account for 79.8% of the inventoried area. However, spatial extent does not necessarily reflect environmental relevance: washed ore represents only 1.8% of the area but displays very high integrated reactivity. Residual sulfides and secondary alteration products in representative units further demonstrate the importance of combining spatial delineation with mineralogical and weathering information. The methodological contribution lies in linking the geometry of individual waste units with information on origin, material characteristics, mineralogy, weathering, and reactivity within a common spatial framework. This provides a consistent basis for comparing heterogeneous mine wastes and supporting environmental screening, targeted investigation, and rehabilitation planning. The workflow can be adapted to different geological, mining, environmental, and data conditions.

Keywords: historical mine wastes; cartographic inventory; unit-based characterization; geospatial analysis; UAV; environmental rehabilitation; Iberian Pyrite Belt

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1. Introduction

Mining has played a major role in economic and industrial development, but it has also left extensive environmental legacies, particularly in historical mining districts where extraction and ore-processing activities preceded modern environmental regulation. Among the most persistent consequences are large accumulations of mining wastes, landscape modification, soil degradation, and contamination of surface and groundwater resources [1–3]. These impacts may persist long after mine closure, making the characterization and management of historical mine wastes a major challenge for environmental rehabilitation.

Mine-waste deposits are inherently heterogeneous. Their environmental behaviour depends on multiple interacting properties, including origin, mineralogical and chemical com-

position, grain size, degree of weathering, and spatial relationships with drainage systems and other environmental receptors. This is particularly relevant for sulfide-bearing wastes, where exposure to atmospheric conditions promotes sulfide oxidation and acid mine drainage (AMD), with associated release of acidity, sulfate, metals, and metalloids [2,4]. Mineralogy and particle-size distribution may strongly influence this behaviour, particularly through the abundance, distribution, and degree of liberation of sulfide and neutralizing minerals [5,6]. Understanding the environmental significance of historical mine wastes therefore requires not only determining their composition and weathering state, but also establishing where different materials occur, how they are spatially organised, and how they relate to the broader mining landscape.

Mineralogical and geochemical investigations provide essential information on waste composition, alteration processes, and contaminant-release potential. However, analytical characterization alone does not necessarily capture the spatial complexity of historical mining sites, where wastes generated during successive phases of extraction, processing, metallurgical activity, transport, and material reuse may coexist within relatively restricted areas. Spatial heterogeneity itself may be environmentally relevant: variations in the distribution of sulfide and carbonate minerals within waste-rock piles can generate local differences in acid-generation potential [7]. Conversely, conventional cartographic inventories may establish the location and extent of waste deposits without adequately representing differences in their origin, composition, weathering characteristics, or environmental significance. Bridging spatial inventory and material characterization is therefore an important methodological requirement for the assessment of complex historical mining landscapes.

Recent developments in remote sensing, UAV photogrammetry, high-resolution terrain analysis, and GIS have considerably expanded the possibilities for identifying, delineating, and characterizing mining wastes. Remote-sensing approaches have successfully identified and georeferenced mine-waste deposits and provided information relevant to subsequent remediation planning [8]. Increasingly integrated approaches combine high-resolution spatial information with field, geochemical, and environmental observations. In the Iberian Pyrite Belt (IPB), UAV photogrammetry combined with mine-waste characterization and water-quality data has been used to investigate waste distribution, erosion pathways, runoff, and contaminant dispersion [9]. At a broader scale, Ramírez-Pérez et al. [10] developed a UAV-based volumetric inventory across 12 IPB mining areas, combining estimates of waste volume and mass with chemical characterization to assess the magnitude and resource potential of abandoned mining wastes. More detailed studies have integrated UAV-derived volumetric information with mineralogical, geochemical, and sequential-extraction data to assess contaminant mobility and critical-raw-material potential in contrasting mine-waste deposits [11].

These studies demonstrate an important progression from purely descriptive mapping or deposit-specific analytical characterization towards increasingly integrated assessments of mine wastes. They also show that neither the use of geospatial technologies nor their combination with analytical information is methodologically novel in itself. However, the primary objectives of existing approaches commonly concern waste detection, volumetric estimation, contaminant mapping and dispersion, geochemical behaviour, or resource evaluation. Comparatively less attention has been given to structuring these complementary sources of information into detailed cartographic inventories in which individually delineated waste units constitute the basic spatial entities and are systematically described by origin, physical characteristics, mineralogical evidence of alteration, and environmentally relevant attributes. Such an approach can provide an intermedi-

ate methodological level between regional-scale inventories and detailed deposit-specific environmental investigations.

This intermediate scale is particularly relevant in complex historical mining districts. Waste accumulations generated during successive phases of extraction, ore processing, metallurgical activity, and material relocation may differ substantially in composition and environmental behaviour even when located in proximity. Their spatial extent alone may therefore not fully indicate environmental relevance. Relatively small deposits containing fine-grained or sulfide-rich processing residues may show stronger evidence of sulfide oxidation and acid-generation potential than much larger accumulations dominated by comparatively less reactive excavation materials. A spatial inventory that preserves these differences at the level of individual waste units can provide the basis for directing subsequent environmental investigation and rehabilitation planning.

The Iberian Pyrite Belt provides a particularly suitable setting in which to develop and test such an approach. Centuries of mining have generated extensive and heterogeneous accumulations of sulfide-bearing wastes throughout southern Portugal and southwestern Spain [9,10,12–15]. Their oxidation contributes to widespread AMD and associated impacts on soils, surface waters, and aquatic ecosystems [13,16]. Within the Portuguese sector of the IPB, the São Domingos Mine represents an especially complex historical mining landscape resulting from successive phases of extraction, ore processing, metallurgical activity, waste deposition, and subsequent material redistribution.

São Domingos has been extensively investigated from hydrochemical, mineralogical, geochemical, and ecological perspectives [17–23]. It is also recognised as a priority abandoned mining site for environmental rehabilitation in Portugal. Rather than representing an insufficiently characterized mining site, this substantial body of previous knowledge makes São Domingos particularly appropriate for testing an integrated inventory approach. The methodological challenge is therefore to organise the heterogeneous waste materials preserved across the mining complex within a coherent spatial framework capable of distinguishing individual waste units and relating their spatial occurrence to their origin, physical properties, mineralogical characteristics, degree of weathering, and environmentally relevant features.

Against this background, this study aims to develop and demonstrate an integrated methodological approach for the detailed inventory and cartographic characterization of solid mining wastes, using the São Domingos mining complex as a case study. The workflow follows a sequential approach combining spatial-data interpretation, UAV imagery and high-resolution terrain information, field mapping and validation, targeted laboratory characterization, and GIS integration to identify, delineate, classify, and environmentally contextualize individual waste units. Laboratory data primarily support field interpretation and waste classification rather than providing an exhaustive geochemical assessment of each deposit.

The methodological contribution lies in structuring these complementary information sources at the scale of individually delineated waste units. Rather than treating geospatial, field, mineralogical, and geochemical data as parallel datasets, the proposed workflow integrates them sequentially within a common GIS framework to produce a reproducible, updateable, and spatially explicit inventory. AMD channels, acidic ponds, and contaminated waters are considered environmental manifestations of waste weathering and contaminant dispersion and are therefore not included in the solid-waste typology. The resulting inventory is intended as a first-stage spatial process for directing subsequent environmental investigation, monitoring, and rehabilitation planning, rather than as a substitute for detailed geochemical, hydrogeological, geotechnical, or formal risk assessment. By applying it at São Domingos, the study also examines its potential transferability to

other historical mining districts characterised by heterogeneous and spatially complex waste accumulations.

2. Study Area

2.1. Geological Setting

The São Domingos mining complex is located in southeastern Portugal, approximately 17 km northeast of Mértola, within the Portuguese sector of the Iberian Pyrite Belt (IPB), one of the world's major volcanogenic massive sulfide (VMS) provinces (Figure 1). The IPB forms part of the South Portuguese Zone of the Iberian Massif and comprises a Paleozoic volcano-sedimentary succession hosting numerous polymetallic massive sulfide deposits [15].

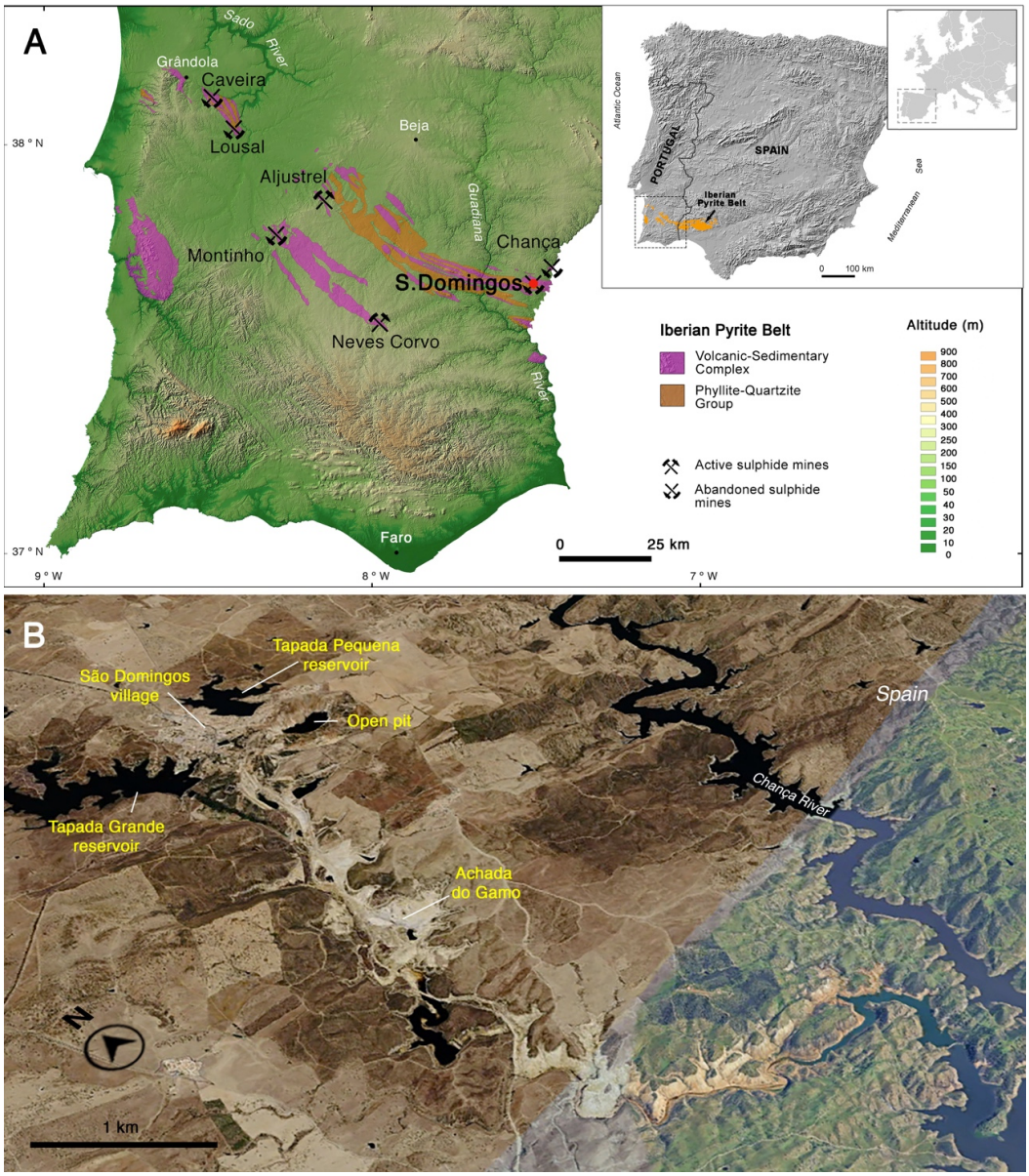


Figure 1. Location and geological setting of the São Domingos mining complex within the Portuguese sector of the Iberian Pyrite Belt (**A**); aerial view (Landsat/Copernicus imagery obtained from Google Earth; altitude 7 km), showing the main locations referred to in the study (**B**).

The São Domingos orebody is hosted by the Volcano-Sedimentary Complex and consists of a subvertical massive sulfide body dominated by pyrite, with chalcopyrite,

sphalerite, galena, arsenopyrite, and other sulfide and sulfosalt minerals [24,25]. Supergene alteration of the upper part of the orebody produced a well-developed gossan, which constituted an important resource during early mining phases [25]. The combination of sulfide-rich ore, associated volcanic and metasedimentary host rocks, and materials generated during extraction and processing resulted in waste deposits with markedly different lithological, mineralogical, and physical characteristics.

Following exposure to atmospheric conditions, sulfide-bearing wastes have undergone extensive oxidation, contributing to AMD generation and the mobilisation of potentially toxic elements [18,20–22]. This geological and mineralogical diversity is directly relevant to the present inventory because it provides the primary source of the contrasting materials subsequently classified as extraction, processing, and metallurgical waste units.

2.2. Mining History and Environmental Legacy

Mining at São Domingos extended over several historical periods, resulting in successive phases of extraction, processing, waste deposition, and material redistribution. Exploitation dates back to at least the Chalcolithic period, while substantial mining activity occurred during Roman occupation. Roman workings targeted mainly the oxidised upper part of the orebody, particularly the gossan, for the recovery of Cu, Ag, and Au [25–27]. Archaeological remains associated with these workings are still preserved within the mining complex.

The most intensive transformation of the site occurred during industrial exploitation between 1857 and 1966 [25,28,29]. Mining progressively developed a large open pit, approximately 120 m deep, together with an extensive underground network reaching depths of approximately 420 m [25]. Ore extraction and beneficiation were accompanied by transport, crushing, sorting, leaching, roasting, and other metallurgical operations. These activities generated substantial volumes of materials with contrasting origins and characteristics, including coarse excavation wastes, host-rock fragments, gossan-derived materials, fine processing residues, washed ore, and heterogeneous industrial wastes.

Mining operations also produced a strongly structured anthropogenic landscape. Waste deposits accumulated around the open pit and processing areas, whereas other mining materials were subsequently relocated and reused in embankments, transport routes, platforms, and terrain levelling. In the terminology adopted in the present study, these relocated and reused mine-waste materials are designated as landfill deposits, consistent with previous waste mapping at São Domingos [25]. The Achada do Gamo processing area, railway infrastructure, leaching and roasting facilities, and associated hydraulic structures therefore contributed not only to generating different waste materials but also to their current spatial distribution across the mining complex.

The Tapada Grande and Tapada Pequena reservoirs (Figure 1) were constructed to provide water for mining and ore-processing activities and formed part of the hydraulic system developed during industrial exploitation. Together with the flooded open pit, extensive waste deposits, industrial platforms, and abandoned infrastructure, these features define the present-day mining landscape (Figure 2).

Historical mining and ore-processing activities affected approximately 296 ha of the São Domingos area [30]. Extensive waste deposits remain exposed to weathering, and sulfide-bearing materials continue to contribute to AMD generation and the mobilisation of potentially toxic elements [18,20–22]. These processes, together with the spatial complexity inherited from successive mining and processing activities, have made São Domingos an important site for environmental investigation and rehabilitation.

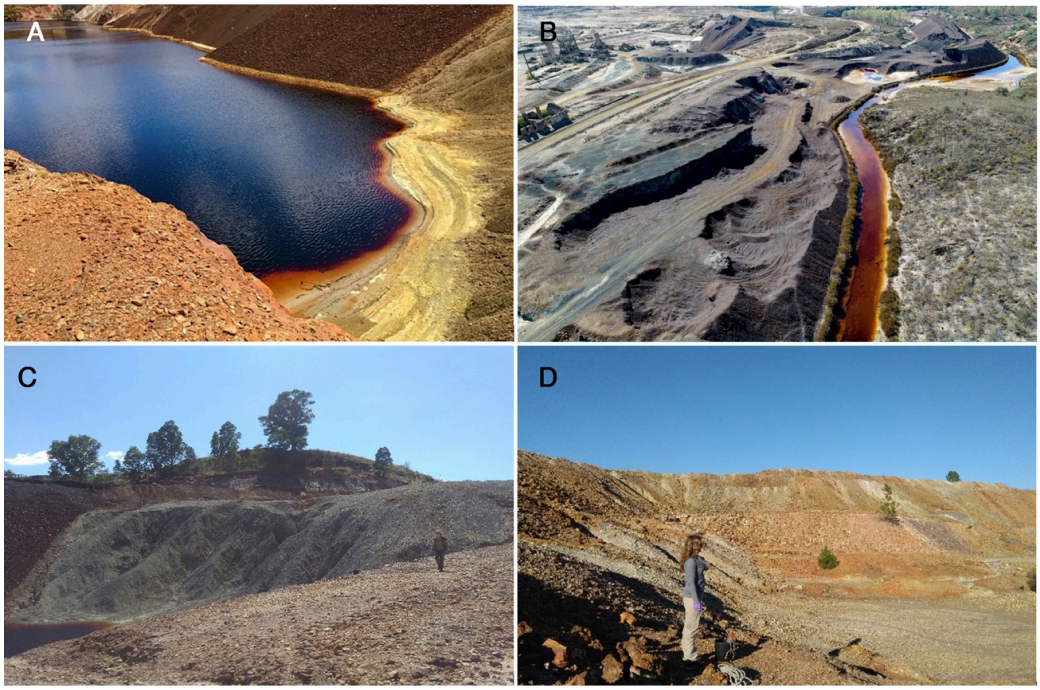


Figure 2. Main landscape elements of the São Domingos mining complex illustrating the environmental legacy of historical mining activities: (**A**) S. Domingos open pit; (**B**) Aerial view of the Achada do Gamo industrial processing area; (**C**) waste dump near the São Domingos open pit; (**D**) landfill materials between the northern sector and the Achada do Gamo industrial area.

The present study focuses on the sector containing the principal historical extraction and processing infrastructures and the major waste accumulations (Figure 1). This sector encompasses the open pit, the Achada do Gamo industrial area, former transport and processing zones, and the main areas of waste deposition and subsequent material redistribution. It therefore provides a spatially and compositionally heterogeneous setting for developing and testing the proposed cartographic inventory.

3. Materials and Methods

3.1. Methodological Approach

The methodological approach was designed to produce a detailed, unit-based cartographic inventory of solid mining wastes by progressively integrating spatial, field, and analytical information. The inventory used the individual waste unit as its basic spatial and descriptive entity. A waste unit was defined as a spatially delineable accumulation of mine-derived solid material that could be distinguished from adjacent materials on the basis of its location and boundaries, origin, dominant material composition, physical characteristics, or evidence of weathering.

The workflow comprised four sequential and complementary stages (Figure 3): (i) compilation and interpretation of spatial datasets for the preliminary identification and delineation of potential waste accumulations; (ii) field verification of their boundaries and characterization of the constituent materials; (iii) targeted laboratory analyses to support and validate the interpretation and classification of representative waste materials; and (iv) integration of spatial, field, and analytical information within a GIS to establish the final waste-unit classification and cartographic inventory.

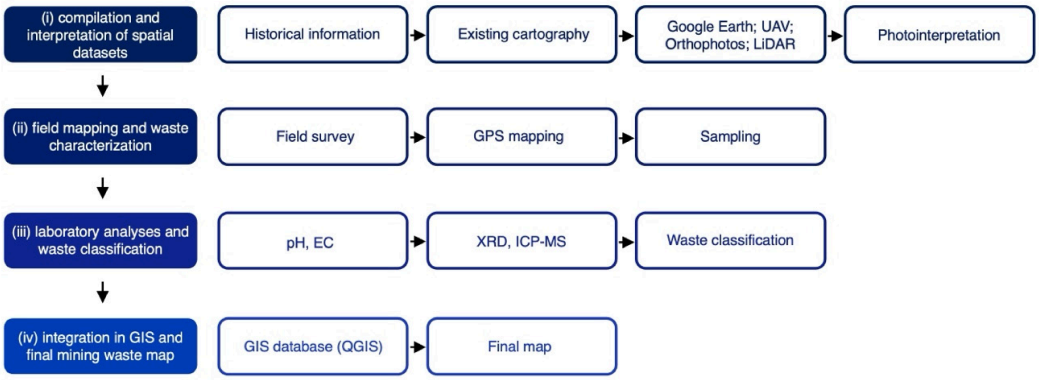


Figure 3. Integrated methodological workflow adopted for the inventory, characterization and cartographic mapping of mining wastes.

The workflow followed a progressive refinement approach. Spatial information provided the initial geometry and context of potential waste units, while field observations confirmed or modified their boundaries and identified differences in origin, dominant lithology, grain size, surface characteristics, and degree of weathering. Mineralogical and geochemical analyses provided complementary evidence to support the interpretation and classification of representative waste materials. Laboratory characterization served as supporting information rather than a requirement for defining every mapped unit.

Waste units were differentiated when spatial and field evidence indicated a meaningful change in the dominant characteristics of the deposited material. Conversely, spatially contiguous materials displaying comparable origin, composition, physical characteristics, and weathering features were treated as a single unit. This procedure allowed the mapped polygons to represent materially interpretable waste accumulations rather than arbitrary subdivisions of the mining landscape.

The classification was restricted to solid mine-waste deposits that could be identified and spatially delineated through the combined interpretation of spatial datasets and field observations. AMD channels, acidic ponds, and AMD-affected flooded areas were mapped as complementary environmental features (Figure S1) but were excluded from the waste typology because they represent manifestations of waste weathering and contaminant transport rather than solid waste units.

For each delineated unit, the GIS database integrated its spatial geometry with descriptive attributes derived from field observations and, where available, laboratory analyses. These included waste origin, dominant material or lithology, grain-size characteristics, mineralogical composition, degree of weathering, and field evidence of sulfide oxidation and secondary mineral formation. Waste reactivity was incorporated as an additional screening attribute based on paste pH and complementary field and mineralogical evidence of sulfide oxidation and weathering, as detailed below.

The resulting inventory combines the spatial individuality of each waste accumulation with information on its origin, physical and mineralogical characteristics, weathering state, and integrated reactivity. By organizing these attributes at the scale of individual waste units within a common spatial framework, the approach enables systematic comparison of heterogeneous mine wastes and provides a consistent basis for identifying spatially relevant patterns.

3.2. Compilation of Spatial Datasets

The first stage involved compiling and interpreting complementary spatial datasets to preliminarily identify and delineate potential mine-waste units. Recent aerial imagery available through Google Earth was initially examined to identify disturbed surfaces, major

waste accumulations, mining infrastructures, and spatial contrasts potentially associated with different waste materials. The combined use of high-resolution imagery and terrain information has proved particularly useful for the identification and spatial characterization of mine-waste deposits [8–10].

High-resolution UAV imagery acquired at the São Domingos mining complex was used to refine the spatial interpretation. The survey was performed using a DJI Phantom 4 Pro (Shenzhen, Guangdong, China) equipped with a 20 MP digital camera, at a flight altitude of 150 m, with 75% frontal and 70% lateral image overlap. The resulting orthophotomap had a ground sampling distance (GSD) of 4.1 cm/pixel. Further details on flight planning, image acquisition, georeferencing, and photogrammetric processing are provided by Gomes et al. [31]. Oblique UAV photographs were additionally used to support visual interpretation of the mining landscape (Figure 2B).

Airborne LiDAR data with a spatial resolution of 0.5 m [32] were used to complement the image-based interpretation and to obtain a detailed representation of terrain morphology (Figure 4B). Although vegetation cover is generally sparse across the São Domingos mining complex, the LiDAR-derived terrain information was particularly useful for identifying anthropogenic landforms and subtle breaks in slope associated with waste emplacement. Hillshade representations enhanced the visualization of deposit morphology and geomorphological boundaries that were not always clearly distinguishable in aerial imagery alone (Figure 4C).

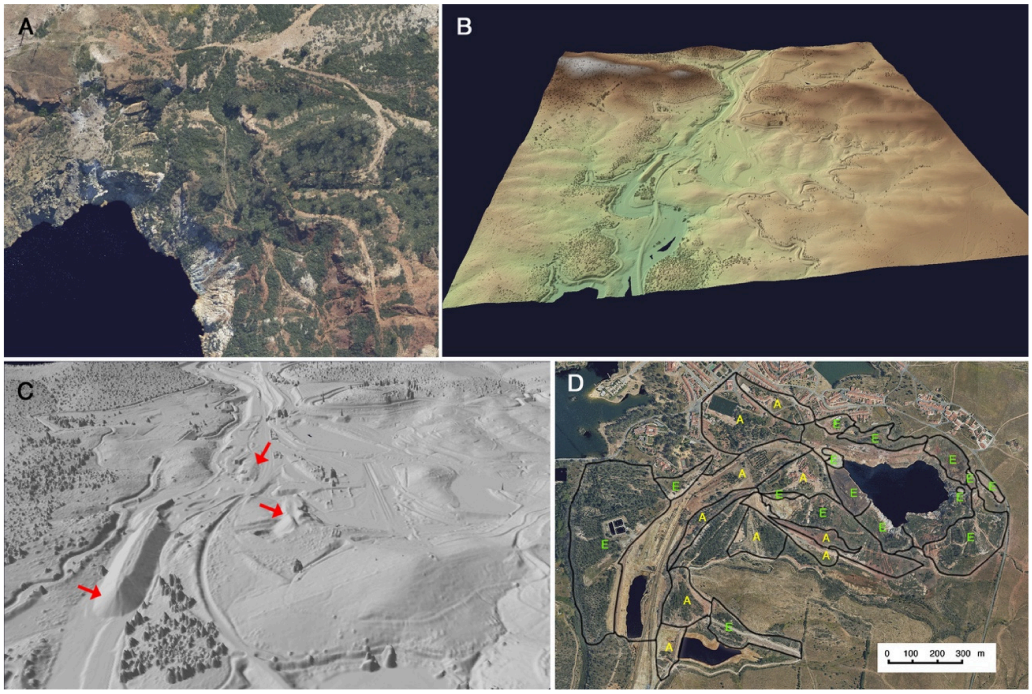


Figure 4. Geospatial datasets used for the identification and delimitation of mining waste units: (**A**) UAV orthophotograph (extract); (**B**) LiDAR-derived digital terrain model (extract); (**C**) hillshade representation highlighting geomorphological features associated with waste deposits (extract); (**D**) preliminary photointerpretation of mining waste units in the northern sector (A–landfill materials; E–waste dumps).

The complementary interpretation of aerial and UAV imagery, LiDAR-derived terrain information and hillshade, and available topographic information was used to establish the preliminary geometry of individual waste units. Boundaries were interpreted from visible changes in surface characteristics, morphology, topographic discontinuities, and spatial relationships with former extraction, processing, transport, and deposition areas. These

preliminary polygons constituted working units for field verification rather than definitive waste boundaries (Figure 4D).

3.3. Field Mapping and Waste Characterization

Field surveys verified the preliminary interpretation of the spatial datasets and refined the delineation and characterization of individual waste units. Preliminary boundaries identified from aerial imagery and terrain information were checked in the field using a Garmin GNSS receiver and were modified where changes in material characteristics or deposit morphology indicated that the initial delineation did not adequately represent the waste accumulation.

Each waste unit was characterized according to a consistent set of field attributes, including inferred origin, dominant lithology or material type, grain size, colour, geomorphological expression, degree of weathering, and visible evidence of geochemical reactivity. Particular attention was given to sulfide occurrence, oxidation products, secondary sulfate minerals, saline efflorescences, and other surface features indicative of sulfide oxidation and acidic conditions. These observations provided field-based evidence for distinguishing materials with contrasting weathering states and potential acid-generating behaviour.

Waste-unit boundaries and classification were refined by combining spatial and field evidence. A preliminary unit was subdivided where field observations revealed spatially coherent differences in origin, dominant material, physical characteristics, or weathering features. Conversely, spatially contiguous materials displaying comparable characteristics and belonging to the same waste accumulation were retained as a single unit. This procedure ensured that the final delineation reflected identifiable differences between waste materials rather than arbitrary spatial subdivisions. Table 1 summarizes the attributes used for waste characterization and classification.

Table 1. Criteria and attributes used for the characterization and classification of mine-waste units.

Attribute	Description/Information Recorded	Source
Origin	Mining/extraction, processing, metallurgical, or relocated/reused mine waste	Historical information and field interpretation
Dominant material/lithology	Predominant rock or waste material	Field observation
Grain size	Predominant grain-size class/characteristics	Field observation
Surface characteristics	Colour and distinctive morphological or surface features	Field observation
Weathering	Degree and visible features of material alteration	Field observation
Geochemical reactivity indicators	Oxidation products, secondary minerals, sulfate efflorescences, and other evidence of acidic conditions	Field observation
Mineralogy	Dominant mineral phases in representative material	Laboratory analysis
Integrated reactivity	Comparative reactivity assessment based on paste pH and supporting mineralogical and field evidence	Laboratory analysis and integrated interpretation [31]

3.4. Laboratory Analyses

Representative samples of the main waste materials were collected during field surveys to support the characterization and interpretation of the mapped waste units. Laboratory analyses included pH and electrical conductivity (EC), mineralogical characterization by X-ray diffraction (XRD), and geochemical analysis of selected samples.

pH and EC were determined using a solid-to-water ratio of 1:2.5. Paste pH was used as a screening indicator of the acid-generating reactivity of the waste materials, following the approach developed for the São Domingos mining complex by Gomes et al. [33]. Together with mineralogical and field evidence of sulfide oxidation and weathering, these data

supported an integrated comparative assessment of waste reactivity. Integrated reactivity is therefore used as a comparative screening attribute within the inventory system and should not be interpreted as a substitute for standardized acid–base accounting, kinetic testing, or site-specific environmental risk assessment.

Mineralogical characterization was performed by X-ray diffraction (XRD) on selected samples representative of the principal waste materials, using a Philips PW1710 diffractometer (APD-3.6j version) with Cu-Kα radiation, 40 kV voltage, and 20 mA (Philips, Amsterdam, The Netherlands). These analyses identified the dominant mineral phases, with particular attention to residual sulfides and secondary minerals associated with weathering and sulfide oxidation. Geochemical analyses were performed by inductively coupled plasma mass spectrometry (ICP-MS) following aqua regia digestion of the <2 mm fraction. Prior to analysis, samples were dried, sieved, and ground in an agate mill. Activation Laboratories Ltd. (Actlabs, Ancaster, ON, Canada), an ISO/IEC 17025 [34] accredited laboratory, carried out all analytical determinations. Laboratory quality assurance and quality control (QA/QC) procedures included the routine use of certified reference materials, analytical blanks, and duplicate analyses to monitor analytical accuracy, precision, and potential contamination throughout the analytical process.

Laboratory analyses of representative waste materials complemented the field characterization by providing mineralogical, physicochemical, and geochemical information. The analytical results primarily supported the interpretation of field observations and validated the classification of the mapped waste units.

3.5. GIS Integration and Cartographic Inventory

All spatial and descriptive information was integrated within a Geographic Information System (GIS) using QGIS. Each waste unit was represented as an individual polygon and assigned a unique identifier, linking its spatial geometry to the corresponding field and analytical information.

The preliminary polygons derived from the spatial datasets were updated according to field verification to establish the final boundaries of the waste units. For each unit, the GIS attribute database incorporated information on waste origin, dominant material or lithology, physical characteristics, weathering features, mineralogical composition, geochemical characteristics, and waste reactivity, according to the criteria described in Table 1. Analytical attributes were assigned only where representative laboratory data were available.

The final cartographic inventory combined the spatial delineation of the waste units with their classification and associated attributes. Waste units were grouped according to similarities in origin and dominant material characteristics while retaining their individual spatial identity within the GIS database. This structure allowed examination of the spatial distribution, extent, and characteristics of different waste types at both the individual-unit and waste-category scales. The workflow was designed to be adaptable to mining sites of different spatial extent and waste complexity. Its practical implementation may vary according to site-specific conditions, including waste heterogeneity, accessibility, vegetation cover, topographic complexity, and the availability and resolution of spatial data. These factors may influence the spatial coverage, field verification, and analytical effort required, without changing the overall structure of the workflow.

4. Results

4.1. Spatial Inventory and Distribution of Mine-Waste Units

The integrated mapping identified 40 individual mine-waste units, covering a total area of 148.34 ha within the study area. The inventory comprises 23 waste dumps (E1–E23) and 17 landfill deposits (A1–A17). Waste dumps correspond to accumulations associated

with extraction, ore-processing, and metallurgical activities, whereas landfill deposits comprise mine-derived materials that were subsequently relocated or reused for road construction, embankments, platforms, and terrain levelling.

The mapped units show a heterogeneous spatial distribution across the mining complex. Waste dumps occur mainly around the open pit, former ore-processing facilities, and the Achada do Gamo industrial sector, whereas landfill deposits are more extensively distributed along former transport corridors and in areas of terrain modification. Individual units vary considerably in spatial extent, morphology, dominant material, grain size, surface characteristics, and degree of weathering. Figure 5 presents an enlarged extract of the cartographic inventory, along with representative field examples, to help visualize individual waste units and their contrasting characteristics. The complete cartographic inventory, including all 40 waste units and ancillary mapped features, is provided in Figure S1 (Supplementary Materials).

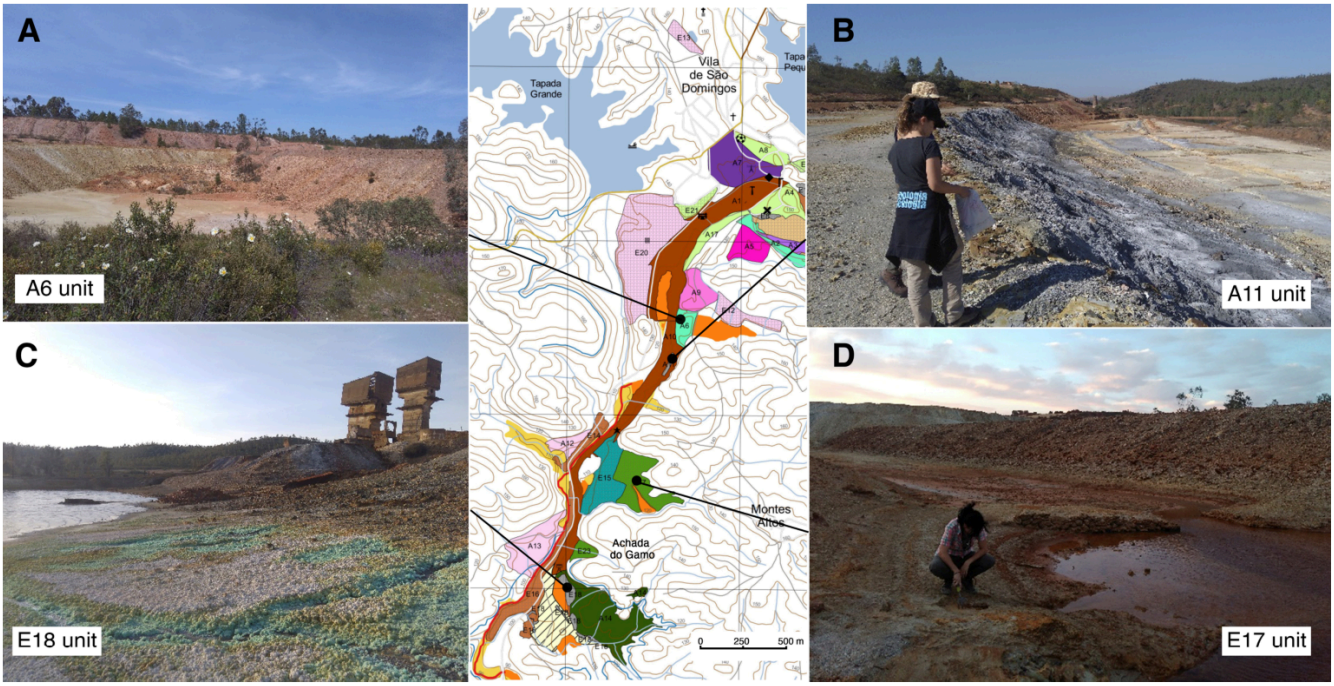


Figure 5. Examples of mine-waste units mapped in the São Domingos mining complex: (**A**) landfill deposit A6, consisting of an accumulation of light-coloured fine-grained sediment derived from the weathering and reworking of surrounding landfill deposits (A1, A9, and A10); (**B**) landfill deposit A11, composed predominantly of washed ore, characterised by a grey colour and abundant saline efflorescence; (**C**) waste dump E18, showing intense salinisation and secondary sulfate mineral assemblages, predominantly copiapite (yellow-green), melanterite (blue), and anglesite (white); and (**D**) waste dump E17, showing accumulations of jarosite (orange-ochre) and saline efflorescence along pond margins. The complete cartographic inventory, including all mapped waste units, the legend, and ancillary features, is provided in Figure S1 (Supplementary Materials).

Based on their origin and dominant material characteristics, the 40 mapped units were classified into seven waste categories: gossan-derived wastes, schist-dominated wastes, volcanic rock-derived wastes, fine-grained weathered sediments, washed ore, mixed processing wastes, and industrial residues. Industrial residues are the largest category, covering 42.97 ha (29.0%), followed by volcanic rock-derived wastes at 37.92 ha (25.6%) and schist-dominated wastes at 37.35 ha (25.2%). Together, these three categories account for 79.8% of the inventoried waste area. Gossan-derived wastes cover 17.29 ha (11.6%), whereas mixed processing wastes account for 5.93 ha (4.0%), fine-grained weathered sediments for 4.15 ha (2.8%), and washed ore for 2.73 ha (1.8%).

The representative units shown in Figure 5 illustrate the range of materials and surface weathering features recorded during field characterization. Unit A6 consists predominantly of light-coloured fine-grained weathered material, whereas A11 is composed predominantly of washed ore and displays abundant saline efflorescence. Unit E18 shows intense surface salinisation and secondary sulfate mineralization, including copiapite, melanterite, and anglesite, while E17 displays jarosite accumulation and saline efflorescence along pond margins.

4.2. Integrated Characterization of Mine-Waste Units

The seven waste categories display contrasting physical, mineralogical, weathering, and reactivity characteristics (Table 2). Gossan-derived wastes are predominantly coarse- to medium-grained and are characterized mainly by goethite, hematite, and quartz. Schist-dominated wastes are generally coarse-grained and contain predominantly quartz and phyllosilicates, whereas volcanic rock-derived wastes are also predominantly coarse-grained and are characterized by chlorite, feldspars, and quartz.

Table 2. Integrated characterization of the mine-waste categories identified in the São Domingos mining complex.

Mining Waste Category	Mapped Units	Area (ha) and %	Dominant Materials	Grain Size	Main Mineralogy	Main Characteristics	Integrated Reactivity
Gossan-derived wastes	E1, E7, A3, A7, A15	17.29 (11.6%)	Gossan	Coarse to medium	Goethite, hematite, quartz	Historical oxidation cap; locally enriched in metals	Moderate
Schists (s.l.)	E12, E13, E20, A5, A9, A12, A13, A16	37.35 (25.2%)	Schists (s.l.)	Coarse	Quartz, phyllosilicates	Predominantly host-rock material; generally low sulfide content	Low
Volcanic rock-derived wastes	E2–E5, E17, E21, E23, A4, A8, A14, A17	37.92 (25.6%)	Volcanic rocks	Coarse	Chlorite, feldspars, quartz	Predominantly host-rock material; locally weathered	Low to moderate
Fine-grained weathered sediments	E6, A2, A6	4.15 (2.8%)	Weathered mixed materials	Fine	Secondary sulfates, clay minerals	Strongly weathered fine-grained material	High
Washed ore	E8, E10, E18, A11	2.73 (1.8%)	Sulfide-rich ore	Fine	Pyrite, chalcopyrite, sphalerite	Sulfide-rich material with conspicuous oxidation features and saline efflorescence	Very high
Mixed processing wastes	E15	5.93 (4%)	Washed ore + country rocks	Fine to medium	Sulfides, altered silicates	Heterogeneous processing material with evidence of sulfide oxidation	High
Industrial residues	E9, E11, E14, E16, E19, E22, A1, A10	42.97 (29%)	Slags, cementation residues	Variable	Iron oxides, slags, secondary minerals	Metallurgical residues with heterogeneous composition	Moderate to high

Fine-grained weathered sediments differ from these coarse waste materials in both texture and alteration features, with secondary sulfates and clay minerals among the identified phases. Washed ore deposits are predominantly fine-grained and retain sulfide minerals, including pyrite, chalcopyrite, and sphalerite. Mixed processing wastes comprise washed ore together with country-rock materials and contain sulfides and altered silicates. Industrial residues, including slags and cementation residues, show the greatest variability in material type and grain size and contain iron oxides, slags, and secondary minerals.

The integrated characterization also distinguishes differences in reactivity among the waste categories. Schist-dominated wastes show low reactivity, whereas volcanic rock-derived wastes range from low to moderate reactivity and gossan-derived wastes show moderate reactivity. Fine-grained weathered sediments and mixed processing wastes show high reactivity, while washed ore is characterized by very high reactivity. Industrial residues show a broader range, from moderate to high, consistent with their heterogeneous composition. These differences occur together with contrasting field and mineralogical evidence of weathering and sulfide oxidation, including the occurrence of secondary sulfate minerals and saline efflorescence in several mapped units.

5. Discussion

5.1. From Waste Mapping to Unit-Based Integrated Characterization

The results obtained at São Domingos show that a cartographic inventory of historical mine wastes can provide substantially more information than the location and spatial extent of waste deposits. By treating each waste accumulation as an individual spatial entity and linking its geometry to information on origin, material characteristics, mineralogy, weathering, and reactivity, the inventory provides a structured representation of the heterogeneity of the mining landscape. This unit-based approach is particularly relevant at historical mining sites, where successive phases of extraction, ore processing, metallurgical activity, and material redistribution have generated spatially complex assemblages of wastes with contrasting characteristics.

Recent developments in mine-waste investigation demonstrate the increasing use of remote sensing, UAV-based surveys, geospatial analysis, and mineralogical and geochemical characterization to describe waste deposits at different spatial and analytical scales [5–11]. Remote sensing has proved effective for the identification and spatial delineation of mine wastes [8], while UAV photogrammetry can provide high-resolution information on waste morphology, spatial distribution, and volume [9,10]. In the IPB, for example, Ramírez-Pérez et al. [10] recently used UAV-derived elevation models to establish a volumetric inventory of waste accumulations across 12 mining sites, complemented by chemical characterization and estimates of their resource potential. Such approaches demonstrate the considerable value of geospatial information for establishing the distribution and magnitude of historical mine-waste deposits.

Spatial delineation alone, however, cannot fully represent the heterogeneity that controls the behaviour of mine wastes. Variations in grain size, sulfide abundance, neutralizing minerals, and weathering products may occur both among and within individual deposits [5–7]. Qiu and Pabst [6], for example, demonstrated marked particle-size segregation and lateral heterogeneity within a single waste-rock pile, while Bao et al. [7] showed that the spatial distribution of sulfide and carbonate minerals may generate localized differences in acid-generation potential. Detailed mineralogical characterization similarly indicates that the abundance, liberation, and distribution of sulfides and neutralizing phases strongly influence waste-rock reactivity [5]. These findings underline the importance of complementing spatial mapping with information describing the nature and alteration state of the mapped materials.

Integrated studies in legacy mining areas further show the value of relating waste characteristics to their spatial and environmental context. At the Trimpancho mining complex in the Iberian Pyrite Belt, the combination of UAV photogrammetry, mine-waste characterization, and hydrochemical information revealed marked contrasts between waste deposits and their contribution to erosion, drainage, and contaminant dispersion [9]. Subsequent mineralogical and geochemical characterization of contrasting deposits at the same

site showed that wastes occurring within a single mining complex may differ substantially in mineral assemblages, contaminant mobility, and overall geochemical behaviour [11].

The methodological contribution of the present approach therefore lies less in the individual techniques employed than in the way complementary information is organized at the scale of the individual waste unit. Remote sensing and terrain information provide the initial spatial framework; field observations verify boundaries and distinguish materials according to origin, physical characteristics, and weathering features; and targeted mineralogical and geochemical analyses provide additional evidence for interpreting representative materials. This sequential integration differs from using spatial and analytical techniques as parallel sources of information because the resulting attributes remain explicitly associated with individually delineated waste units within a common GIS procedure.

This unit-based organization is also consistent with the broader development of geospatial mine-waste inventories in which mapped waste features are increasingly associated with descriptive attributes. The recently released U.S. Geological Survey National Mine Waste Inventory, for example, represents mine-waste features as points and polygons linked to information on location, size, commodity, and mineralogy [35]. Although developed at a substantially broader spatial scale and for different objectives, such initiatives reinforce the value of structuring mine-waste information around identifiable spatial entities to which progressively more detailed attributes can be associated.

At São Domingos, this structure is particularly relevant because the present distribution of mine wastes reflects successive periods of mining and the extensive spatial reorganization associated with industrial exploitation. Extraction wastes, processing residues, metallurgical materials, and subsequently relocated mine wastes occur in close spatial association. Consequently, deposits with different origins may display similar surface expressions, whereas apparently continuous accumulations may contain materials with contrasting characteristics. The combined use of spatial interpretation and field verification therefore reduces the risk of classifying waste materials solely from surface appearance or deposit geometry and allows historical information on mining and processing activities to contribute to their interpretation.

The resulting inventory can thus be considered a spatially structured characterization process rather than a conventional waste map. By preserving the individuality of mapped waste units while associating them with information obtained at different observational and analytical scales, the approach accommodates the heterogeneity characteristic of historical mining landscapes. This unit-based organization also provides the basis for examining whether spatial extent, material type, mineralogical alteration, and reactivity convey consistent or contrasting information on the environmental significance of the different waste categories.

5.2. Environmental Significance and Implications for Rehabilitation

The spatial distribution of the waste categories at São Domingos shows that the area occupied by a deposit is not necessarily indicative of its environmental importance. Industrial residues, volcanic rock-derived wastes, and schist-dominated wastes together account for 79.8% of the inventoried area, whereas washed ore represents only 1.8%. However, the integrated characterization reveals a different pattern in terms of reactivity. Schist-dominated wastes show low reactivity and volcanic rock-derived wastes range from low to moderate, whereas washed ore shows very high reactivity. Fine-grained weathered sediments and mixed processing wastes, which also occupy comparatively limited areas, show high reactivity. Spatial extent alone therefore provides an incomplete basis for differentiating mine wastes in terms of their potential environmental relevance.

These contrasts reflect differences in waste composition, mineralogy, texture, and weathering. The relatively low reactivity of schist-dominated wastes is consistent with their predominantly host-rock composition and generally low sulfide content, whereas washed ore retains sulfide minerals, including pyrite, chalcopyrite, and sphalerite. Mineralogical composition and the occurrence and accessibility of sulfide and neutralizing phases are major controls on acid generation and metal(loid) release from mine wastes [5–7,36]. The occurrence of jarosite, copiapite, melanterite, and other saline efflorescences in representative units at São Domingos provides evidence of oxidative weathering of sulfide-bearing materials. Beyond their mineralogical identification, these secondary phases record the evolution of waste materials under changing geochemical conditions and may act as temporary reservoirs for acidity, sulfate, and potentially toxic elements. Their subsequent dissolution or transformation may promote remobilization of stored constituents in response to changing hydrological or geochemical conditions, linking mineralogical evolution to the environmental behaviour of mine wastes [36,37].

Physical characteristics add another dimension to this environmental differentiation. Fine-grained weathered sediments and processing wastes combine high reactivity with characteristics that may favour erosion and redistribution, whereas coarse host-rock wastes may occupy considerably larger areas while displaying lower reactivity. Similar relationships between mineralogical composition, texture, weathering, and environmental behaviour have been reported in other legacy mining settings [9,11,38]. The São Domingos inventory therefore highlights the importance of integrating spatial distribution, waste characteristics, and weathering state rather than relying on spatial extent alone to infer environmental relevance.

These differences have practical implications for rehabilitation planning. By combining waste-unit geometry with material type, mineralogical evidence of alteration, and integrated reactivity, the inventory can help identify units requiring different types of subsequent investigation. A small but highly reactive unit may, for example, warrant detailed geochemical or hydrogeochemical characterization despite its limited spatial extent, whereas other units may require greater attention to contaminant mobility, erosion, or material redistribution.

Waste typology can also inform the subsequent selection and design of rehabilitation measures, since grain size, mineralogy, weathering state, and sulfide occurrence influence contaminant-generation processes and the suitability of management options [36,38]. Thus, the inventory supports environmental screening and rehabilitation planning without assigning intervention priorities solely on the basis of waste category, spatial extent, or reactivity. Because these characteristics remain associated with individual spatial entities within the GIS, additional geochemical, hydrogeological, or environmental information can be progressively incorporated as it becomes available. This provides a flexible spatial framework for refining the characterization of individual waste units and supporting targeted investigation and future reassessment.

5.3. Lessons Learned and Future Developments

The application of the framework at São Domingos provides several practical lessons for the development of mine-waste inventories at other historical mining sites. First, the historical context of mining and ore processing is essential for interpreting present-day waste distribution. At São Domingos, successive phases of extraction, processing, transport, and material reuse produced a landscape in which the current position of a waste deposit does not necessarily correspond to its original place of generation. Historical information should therefore be considered alongside spatial and field evidence when reconstructing waste origin and interpreting complex depositional patterns.

A second lesson concerns the level and type of spatial information required for waste delineation. High-resolution UAV imagery proved particularly effective for identifying surface contrasts and deposit boundaries, while LiDAR-derived terrain information improved the recognition of anthropogenic landforms and subtle morphological discontinuities. Previous studies similarly demonstrate the value of high-resolution remote sensing and UAV-derived topography for delineating and characterizing mine-waste deposits [8–10]. Their relative contribution will nevertheless depend on site conditions. At sites with greater vegetation cover, complex topography, or poor surface contrast, terrain information may become particularly useful, whereas in open mining landscapes high-resolution imagery may provide much of the information required for preliminary delineation. The workflow should therefore be adapted to the characteristics of the mining landscape rather than prescribing a fixed combination of spatial datasets.

A similar principle applies to analytical characterization. Comprehensive laboratory analysis of every mapped unit is neither necessary nor always feasible for establishing a useful inventory. At São Domingos, targeted analyses of representative materials provided sufficient information to support field interpretation and differentiate the principal waste types. This is consistent with studies showing that mine-waste deposits may display substantial physical, mineralogical, and geochemical heterogeneity [5,6,11]. Analytical effort can therefore be scaled according to waste heterogeneity, available information, and the objectives of the investigation, with more detailed characterization directed towards selected units where additional information is required.

Transferability should consequently be understood in terms of the workflow rather than a fixed waste classification. The sequence of spatial identification, field verification, targeted characterization, and GIS integration can be adapted to other historical mining districts, whereas the attributes used to distinguish waste units should reflect local geology, ore type, processing history, environmental setting, and data availability. Mine-waste characteristics are strongly conditioned by the nature of the mineral deposit, extraction and processing methods, and subsequent weathering [36,38]. The seven waste categories identified at São Domingos should therefore be regarded as site-specific expressions of the broader methodological framework rather than as a universal mine-waste classification.

The structured information provided by the inventory may also support subsequent waste-management and regulatory assessments by identifying and spatially locating waste units for which more detailed characterization may be required. This is consistent with the importance attributed to waste characterization and classification within mining-waste regulatory frameworks [39]. The same spatial framework may also assist in selecting waste units for further investigation of their potential for resource recovery, although such evaluation would require dedicated mineralogical, geochemical, volumetric, metallurgical, and techno-economic assessment.

Future development can build on this adaptable structure. Multispectral and spectroradiometric data offer opportunities to improve the spatial discrimination of mine-waste and weathering signatures, while three-dimensional approaches can extend surface inventories towards improved characterization of waste geometry and volume [8–10]. At the Mostardeira mine (Portugal), the integration of portable X-ray fluorescence and spectroradiometry with UAV and Sentinel-2 imagery, combined with supervised and unsupervised classification techniques, successfully differentiated mine waste from other surface materials and supported the cartographic representation of contaminated areas [40]. Such developments illustrate how additional spectral and analytical information can progressively enhance mine-waste inventories without changing the fundamental structure of the framework.

6. Conclusions

This study developed and applied a unit-based cartographic framework for the inventory and characterization of solid mine wastes at the historical São Domingos mining complex. The integration of spatial datasets, field observations, targeted mineralogical and geochemical analyses, and GIS enabled the delineation of 40 individual waste units, covering 148.34 ha, and their classification into seven waste categories according to their origin and material characteristics.

The results demonstrate that the spatial extent of mine wastes does not necessarily reflect their environmental relevance. Industrial residues, volcanic rock-derived wastes, and schist-dominated wastes account for most of the inventoried area, whereas washed ore represents only a small proportion but shows very high integrated reactivity. The association of residual sulfides with secondary alteration products in several waste types further highlights the importance of considering mineralogical evolution and weathering alongside spatial distribution and physical characteristics. Thus, inventories based primarily on waste location or extent may overlook relatively small waste accumulations with characteristics indicative of greater environmental reactivity.

By maintaining the individual waste unit as the spatial basis of the inventory, the proposed framework integrates information on waste origin, physical characteristics, mineralogy, weathering, and reactivity. This structure provides a consistent basis for comparing heterogeneous waste materials and for directing subsequent investigation and rehabilitation planning without implying that spatial extent or reactivity alone determines intervention priorities.

The experience at São Domingos also indicates that the approach can be adapted to other historical mining areas. Transferability lies primarily in the workflow—spatial identification, field verification, targeted characterization, and GIS integration—rather than in the specific waste categories established for São Domingos. The level of spatial and analytical detail can therefore be adjusted to local geological, mining, environmental, and data conditions, while additional information can progressively be incorporated into the inventory as required.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/mining6040086/s1, Figure S1: Cartographic inventory of mining wastes in the São Domingos mining complex (Iberian Pyrite Belt, Portugal).

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