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Geochemical and Mineralogical Analysis of Mining Tailings in Mimika Regency for Reutilization Potential Evaluation

Nilam Sry Putri[1]*, **Abd. Rahim**[1]

[1] Department of Mining Engineering, Politeknik Amamapare Timika, Jl. C. Heatubun, Kwamki Baru, Mimika Regency, Central Papua, **Indonesia**

*nilamsryp@gmail.com

Abstract

This study characterizes the geochemical, mineralogical, and morphological properties of mine tailings along the Kali Kabur River in Mimika Regency, Central Papua. The tailings, generated by mining activities, contain valuable metallic minerals, including iron (Fe), copper (Cu), and titanium (Ti). Using X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and Scanning Electron Microscope–Energy Dispersive X-Ray Spectroscopy (SEM–EDS), we identified major oxides (Fe_2O_3, SiO_2, CaO) and minerals (quartz, magnetite, ilmenite, chalcopyrite). Results indicate that the tailings possess potential for reutilization as secondary resources for metal extraction and as raw materials for iron sand production. This research provides novel insights into sustainable tailings management and offers guidance for local industries in the reutilization of mining waste, contributing to circular economy practices.

Keywords: Tailings, Geochemistry, Mineralogy, Reutilization, Fe–Cu–Ti Extraction, Mimika

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1. Introduction

Mimika Regency tailings, like many post-beneficiation wastes, commonly retain economically relevant residuals such as iron (Fe), copper (Cu), and titanium (Ti), and therefore warrant targeted geochemical and mineralogical characterization to evaluate reuse and recovery options [1], [2]. Integrated mineralogical, microstructural (e.g., Scanning Electron Microscopy with Energy Dispersive Spectroscopy, SEM/EDS), and geochemical testing have proven essential to quantify amenable metal phases and inform metallurgy or physical liberation strategies [3].

Characterization also enables non-metallurgical valorization pathways (e.g., engineered aggregates, cementitious materials) and supports lifecycle/circular-economy reuse that has been demonstrated for tailings and industrial wastes [1], [4]. Additionally, identified Ti-bearing phases can contribute to specialty alloy or materials chains if sufficiently concentrated and processed, as titanium microstructure-to-property relationships are critical for various industrial applications [5]. Thus, a program combining bulk geochemistry, mineralogy, liberation testing, and leaching/metallurgical trials is recommended to establish the technical and economic feasibility of recovery and reuse in Mimika [1], [2], [3], [4], [5].

Without effective management, Mimika Regency tailings can generate acid mine drainage (AMD) and metal leaching that contaminate surface water, groundwater, and soils, releasing copper (Cu), iron (Fe), and other toxic metals with long-lasting impacts [6], [7], [8]. Climate, tailings granulometry, beach slope, and supernatant ponding modulate seepage and failure risk, making spatial monitoring of wet tailings essential to reduce environmental harm [9]. Conversely, tailings can retain recoverable metallic phases (e.g., Fe, Cu, Ti) and can be repurposed for metal recovery or construction materials, supporting circular economy outcomes if underpinned by rigorous characterization [10]. Therefore, an integrated program of bulk geochemistry, mineralogy, microstructural liberation testing, and hydrometallurgical/leaching trials—aligned with tailings governance standards like the Global Industry Standard on Tailings Management (GISTM)—is recommended to quantify recovery potential while preventing AMD and long-term liabilities [10].

Mimika tailings are plausibly enriched in residual iron (Fe), copper (Cu), and titanium (Ti) and therefore merit targeted geochemical and mineralogical characterization to assess secondary metal recovery and material reuse [1], [2]. Integrated analyses (bulk geochemistry, X-ray diffraction (XRD)/mineralogy, scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS), liberation and leach/metallurgical tests) are essential to identify amenable mineral phases and processing routes [1], [2], [4]. Without such characterization and management, sulfide-bearing tailings can generate acid mine drainage (AMD) and mobilize copper, iron, and other metals to soils and water bodies [6], [11], [12]. Conversely, characterized tailings have been valorized as aggregates, construction feedstocks, or precursors for advanced materials and metal products (including cupric ferrites and titanium-bearing alloys/nanomaterials) supporting circular economy outcomes if governance and monitoring (e.g., GISTM-aligned) are applied [1], [2], [13]. We therefore recommend a focused Mimika program combining the above analyses, pilot recovery trials, and hydrological/AMD risk assessment to quantify technical and environmental feasibility [1], [6], [10].

While some studies have analyzed the reuse potential of tailings in other regions, no published study was identified that applies an integrated XRD–XRF–SEM/EDS workflow specifically to characterize Mimika Regency tailings; however, tailings elsewhere have been shown to retain recoverable metals such as Fe and Cu, which can be valorized when comprehensively characterized [14], [15]. Proven analytical workflows that utilize bulk XRF geochemistry, XRD mineralogy, and SEM–EDS microstructural analyses can effectively define extractable metal phases and guide metallurgical or material reuse strategies [16], [17], [18]. Since sulfide-bearing tailings present risks of acid mine drainage (AMD) and metal leaching, integrated characterization must be coupled with hydrological and AMD risk assessments to enable safe recovery and foster a circular economy [6], [7]. Therefore, we recommend a targeted program in Mimika using XRF, XRD, SEM–EDS, liberation testing, and leach/metallurgical trials to quantify recovery potential and environmental risk prior to reuse or extraction trials [14], [16].

This study aims to fill this scientific gap by employing a combination of XRD, XRF, and SEM–EDS techniques to analyze the tailings from two depositional sites along the Kali Kabur River. The integration of these methods allows for a more detailed understanding of the tailings' chemical and mineralogical composition, providing valuable insights into the potential reutilization of these materials as secondary resources for metal extraction, such as Fe, Cu, and Ti. This comprehensive approach also contributes to the development of sustainable mining practices by providing evidence for the feasibility of tailings repurposing.

Beyond the scientific contribution, this study has significant environmental implications. The findings have the potential to guide local industries in Mimika, specifically in reducing the environmental pollution associated with tailings and promoting a circular economy. By evaluating the economic feasibility of extracting secondary metals from these tailings, the study presents an opportunity to transform mining waste into valuable resources. In doing so, it aligns with global principles of sustainable mining, which emphasize reducing waste, lowering environmental impact, and enhancing the value of byproducts. The research also lays the foundation for local policy recommendations, encouraging the adoption of more sustainable mining practices that can contribute to the region's long-term economic and environmental health.

2. Methods

This research was conducted along the Kali Kabur River in Mimika Regency, Central Papua, which is a significant site for mining activities, particularly those associated with PT Freeport Indonesia. The river receives tailings discharges from the mining operations, and these tailings often accumulate in different depositional zones along the river system. To ensure that the findings are representative of the overall tailings characteristics in the region, two specific sampling locations, referred to as ST1 and ST2, were selected from mid-edge sections of the Kali Kabur River, as seen in **Figure 1**. These sites were chosen based on their distinct geological and morphological features, which are indicative of different depositional conditions along the river.

Sample Site ST1 was located near a section of the river where tailings are relatively undisturbed, potentially representing more primary tailings material. In contrast, Sample Site ST2 was selected from a more exposed area, likely subject to oxidation and secondary mineralization processes due to periodic air exposure and water level fluctuations. The diversity in environmental exposure and depositional conditions between the two sites makes them representative of the wider tailings distribution within the Kali Kabur River system, and by extension, the larger Mimika mining region.

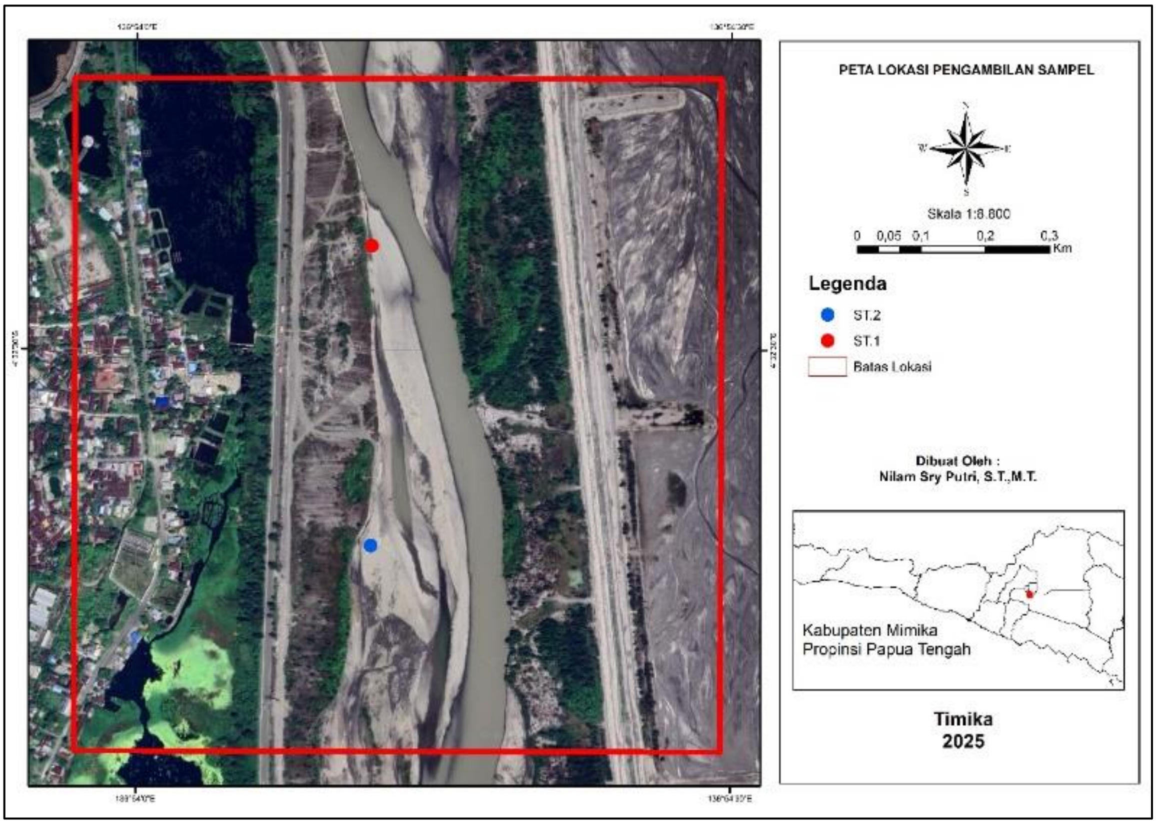

Figure 1. Sampling Location

2.1 Sampling Procedure

The tailings samples were subjected to standard preparation protocols to ensure consistency and accuracy in the laboratory analyses. First, the samples were dried and sieved to a consistent mesh size (100 mesh) to achieve uniform particle size for mineralogical and geochemical testing. The homogenization process aimed to ensure that each sample represented the overall characteristics of the tailings deposit at each site. To further reduce errors, duplicate sample preparations were carried out for each test method.

2.2 Sample Preparation and Standardization

System requirements were collected through interviews with members of the Mina Mulya Fish Farmer Group, Jatimulyo Village, Alian, Kebumen. The farmers reported problems such as unstable water pH, low oxygen levels, and frequent pump failures due to improper water management.

2.3 Laboratory Analysis

To analyze the geochemical and mineralogical composition of the mine tailings, several laboratory techniques were employed to ensure comprehensive characterization. X-ray fluorescence (XRF) analysis on powdered Mimika tailings can be utilized to quantify major and minor oxides, such as Fe2O3, SiO2, CaO, and TiO2, contributing to a comprehensive chemical fingerprint essential for processing and environmental assessment [19]. X-ray diffraction (XRD) analysis of these powders effectively resolves crystalline phases, including quartz, diopside, magnetite, and ilmenite, by matching observed diffraction patterns to standard databases, which is important for identifying mineral hosts of elements like Fe, Cu, and Ti [20]. Scanning electron microscopy with energy dispersive spectroscopy (SEM–EDS) provides microstructural and microchemical context—detailed high-resolution morphology, particle textures, oxidation rims, and fine-grained sulfides such as chalcopyrite and pyrite—which are crucial for predicting mineral liberation and leaching efficiency [20]. An integrated workflow that combines XRF, XRD, and SEM/EDS analysis thus generates a comprehensive geochemical and mineralogical dataset that directly informs recovery strategies, reuse options, and Acid Mine Drainage (AMD) risk mitigation for Mimika tailings [19]. This multi-technique approach allowed for a thorough assessment of both the chemical and mineralogical properties of the tailings.

2.4 Sources of Error and Standardization Protocols

To minimize potential sources of error and ensure the accuracy and reliability of the results, several standardization protocols were followed throughout the study. The samples were carefully homogenized before analysis to ensure uniformity and representativeness of each sample. A 100-mesh particle size was chosen to standardize the preparation of the tailings, ensuring that all samples were treated consistently. In the laboratory, calibration of the instruments was performed according to established standards to reduce the potential for instrumental errors. Multiple replicate analyses were conducted for each sample, and the results were cross-validated using the different analytical methods to ensure reproducibility and minimize variability due to sample handling or testing inconsistencies. Additionally, the presence of outlier data was carefully examined to rule out any contamination or preparation errors. The use of these standardization procedures, along with the careful calibration and repetition of tests, helped ensure that the findings were robust and reliable, providing a sound basis for evaluating the potential reutilization of the tailings.

2.5 Geological and Geographical Representativeness

The two sampling locations, ST1 and ST2, were selected to capture a range of depositional environments within the Kali Kabur River system. ST1, located in an area with lower oxidation exposure, reflects more primary tailings material, while ST2, exposed to periodic air and moisture fluctuations, represents a more altered and oxidized deposit. Together, these locations provide a comprehensive view of the geochemical and mineralogical variability of the tailings across different environmental conditions, making the results of this study applicable to other tailings deposits within the region and potentially to similar mining areas globally.

2.6 Analysis and Evaluation of Tailings Utilization Potential

The characterization data obtained from the XRF, XRD, and SEM–EDS analyses were compared to industrial standards for mineral quality and potential use in secondary metal extraction and industrial applications such as construction and land reclamation. The study also assessed the economic feasibility of utilizing these tailings, considering factors such as mineral concentration, potential recovery methods, and environmental sustainability.

3.Results and Discussion

3.1 XRD Analysis

XRD analysis identified crystalline phases in samples ST1 and ST2 collected from mid–edge sections of Kali Kabur (**Figure 2-3**). ST1 showed strong diffraction peaks for quartz (43.5%), diopside (29.1%), andradite (15.6%), and magnetite (11.8%), indicating preserved host rock characteristics with high crystallinity. ST2 revealed dominant quartz (44.4%), magnetite (33.3%), enstatite (12.7%), ilmenite (4.8%), and hematite (4.7%), reflecting local oxidation in periodically exposed zones and deposition of heavy minerals such as ilmenite in low-turbulence conditions.

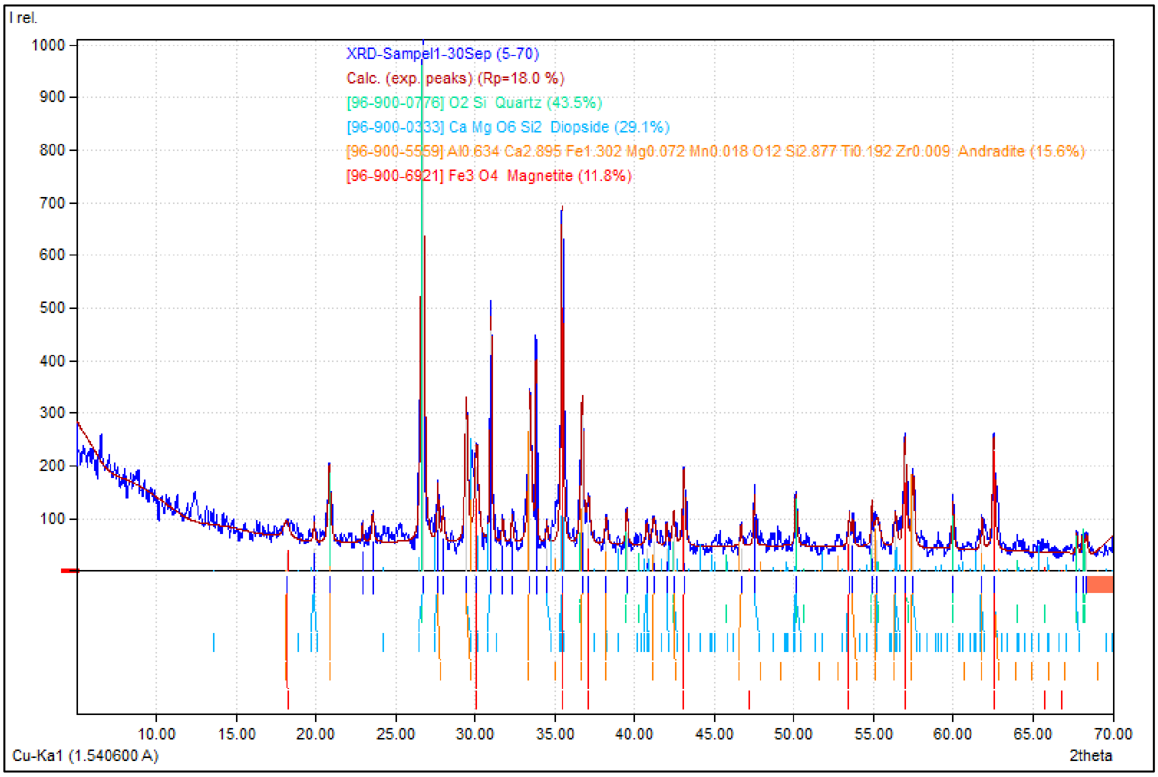

Figure 2. Graphical Abstract illustrating the overall design and workflow of the proposed IoT-based aquaculture monitoring system

The XRD patterns from both ST1 and ST2 demonstrate that the crystalline phases are dominated by quartz, iron oxides, and calcium–magnesium silicates, which are typical of tailings derived from the processing of copper–iron-rich ores. The high proportion of quartz (43–44%) in both samples suggests that the silicate fraction of the original ore and gangue minerals remains stable during processing and post-depositional weathering.

In ST1, the coexistence of diopside and andradite indicates remnants of a skarn-type mineral assemblage, reflecting contact metamorphic conditions between silicate and carbonate protoliths. The presence of magnetite (11.8%) further supports a mineralogical system dominated by Fe–Ca–Si, consistent with Fe-bearing skarn formation. The sharp diffraction peaks imply high crystallinity and low alteration intensity, suggesting that the material at ST1 is relatively unweathered and may have been deposited in less oxidizing, periodically submerged conditions.

In contrast, the mineral phases in ST2 show a compositional shift toward ferruginous and titanium-bearing minerals, with magnetite (33.3%), hematite (4.7%), and ilmenite (4.8%) being predominant. The presence of enstatite (12.7%) instead of diopside suggests a partial transformation of Ca–Mg silicates into Mg–Fe silicates, which may be linked to pH fluctuations and oxidation–reduction reactions occurring in the depositional environment. The observed enrichment of iron oxides (magnetite, hematite) at the tailings surface is consistent with oxidative alteration driven by periodic atmospheric exposure during dry intervals: oxygen-rich conditions promote transformation of Fe-bearing precursors into magnetite and hematite, as demonstrated in laboratory studies where O2 availability controls the pathways of magnetite to maghemite and hematite Kądziołka-Gaweł et al. [21]. Field studies further corroborate that iron mineral oxidation develops on exposed or fractured surfaces where chemical weathering is active, indicating a relationship between these processes and the presence of iron oxides like magnetite and hematite [22], [23]. Tailings studies also document the coexistence of magnetite and hematite phases and note significant analytical challenges in distinguishing them, supporting the interpretation of surface oxidation rather than primary input [24]. Furthermore, tailings hydrodynamics and wet-dry cycling can modulate redox gradients and mineral stability, influencing phase transitions from ST1 to ST2 [9], [19].

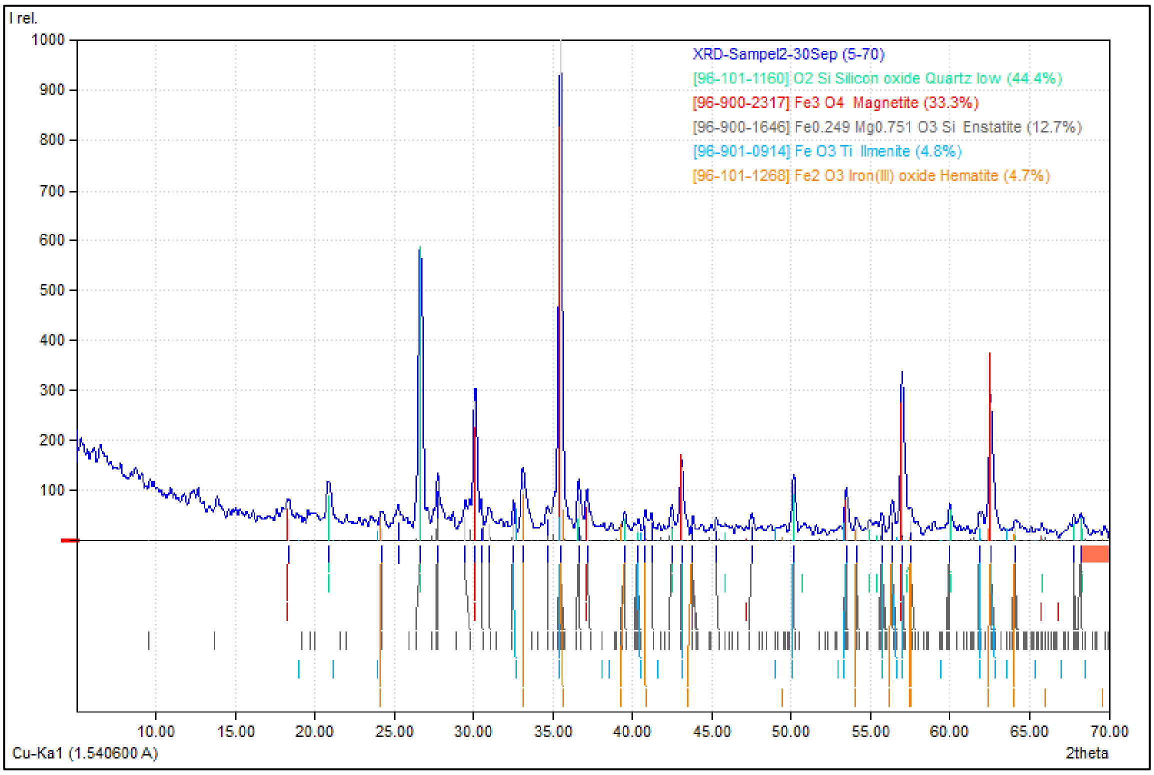

Figure 3. XRD Test Graph of Sample ST2

The surface enrichment of magnetite–hematite and related secondary sulfates in Mimika tailings is consistent with global observations that intermittent ponding and periodic air exposure drive oxidative weathering of sulfide-bearing wastes, producing iron oxides/oxyhydroxides and sulfate crusts [25], [26]. Field cases from Brazil (Fundão/Doce River) and Chilean copper districts document abundant hematite/goethite and oxidative alteration products after tailings exposure, analogous to processes inferred for Mimika under fluctuating redox and hydrodynamic regimes [25], [27]. Studies of abandoned tailings (Taxco, Tanjung) explicitly show pyrite–chalcopyrite weathering to jarosite, gypsum, goethite, and hematite, supporting the pathway from sulfides to iron-rich secondary phases under variable oxygenation [28], [26]. Integrating these insights is therefore essential for acid mine drainage (AMD) mitigation, monitoring, and for evaluating safe reuse and secondary-metal recovery in Mimika within a circular economy framework [25], [27].

3.2 XRF Analysis

Major oxides include SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, and TiO_2 (Table 1). Fe_2O_3 increased significantly from 18.74% in ST1 to 29.12% in ST2, while SiO_2 and CaO decreased, as seen in **Table 1** and **Figure 4**. This indicates localized oxidation enrichment due to fluctuating water levels. The Fe_2O_3/SiO_2 ratio increased from 0.43 to 0.73, confirming ferruginous enrichment. Minor TiO_2 and MnO increases correspond to heavy mineral accumulation in lower-energy depositional zones.

Tabel 1. XRF Test Results

Oxide Components	ST1 (wt%)	ST2 wt%)	Change (%)
SiO_2	43,21	39,88	-3,33
Fe_2O_3	18,74	29,12	10,38
Al_2O_3	9,26	8,45	-0,81
CaO	12,67	6,42	-6,25
MgO	6,31	4,18	-2,13
TiO_2	2,89	3,75	0,86
MnO and others	1,92	2,2	0,28

The XRF results corroborate the mineralogical findings by highlighting chemical trends that reflect oxidation and enrichment processes. The substantial increase of Fe_2O_3 content from 18.74% (ST1) to 29.12% (ST2) corresponds well with the XRD detection of magnetite and hematite as dominant iron-bearing phases. This enrichment is likely caused by the oxidation of Fe^{2+}-bearing minerals to Fe^{3+} oxides, a process favored by alternating wet–dry conditions that promote cyclic redox reactions.

The XRF-observed decline in SiO_2 and CaO, accompanied by an increase in Fe_2O_3/SiO_2 from 0.43 to 0.73, is indicative of mechanical winnowing and chemical depletion of silicate/carbonate phases, alongside gradual ferruginization in low-energy depositional microenvironments. Sedimentological and geochemical studies link the loss of SiO_2 and CaO to the transport/weathering processes, as well as the selective concentration of resilient iron oxides Renani et al. [29]. The observed modest TiO_2 enrichment and any concurrent rise in MnO indicate the concentration of dense Ti-bearing and Mn-oxide phases (e.g., ilmenite, manganese oxides) facilitated by hydraulic sorting and post-depositional preservation in calm zones, as supported by heavy-mineral separation and beneficiation studies [30]. Altogether, these multi-proxy signals suggest localized oxidation, sedimentation, and density-driven enrichment—not broad-scale regional gradients—with the XRF oxides (Fe_2O_3, SiO_2, CaO) acting as robust indicators when sample preparation and pelletization are correctly managed [31].

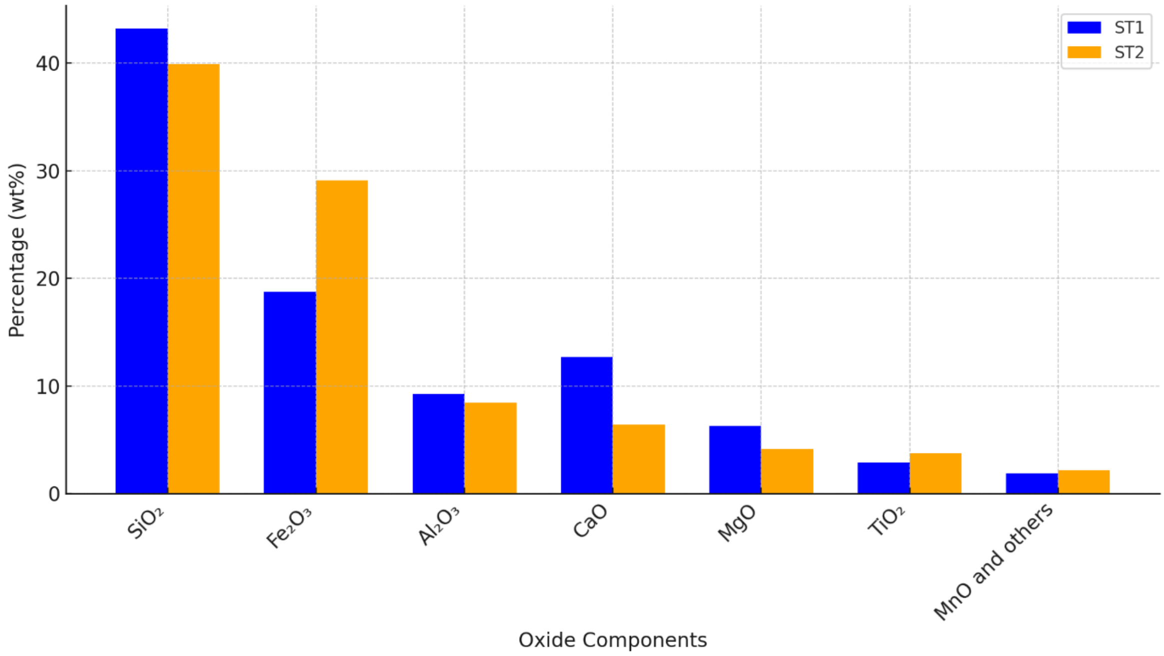

Figure 4. Oxide Composition of Tailings on ST1 and ST2 Samples

3.3 SEM–EDS Analysis

SEM imagery revealed angular to subrounded grains (100–500 μm) in the tailings, with ST1 exhibiting rougher surfaces and primary textures, while ST2 displayed smoother morphology with oxide coatings, indicating secondary oxidation. These differences highlight the varying degrees of alteration between the two sites, likely due to exposure to air and fluctuating moisture conditions over time.

EDS results confirmed the presence of chalcopyrite-like residues (Cu–Fe–S), magnetite/hematite (Fe–O), quartz (Si–O), and ilmenite (Fe–Ti–O). The detection of chalcopyrite in ST1 suggests the retention of residual metallic sulfides, which remain unoxidized and could present opportunities for secondary copper recovery. This indicates that copper recovery techniques, such as flotation or leaching, could be effective in extracting copper from the primary material in ST1, which may still contain significant amounts of chalcopyrite. ST2's dominance of Fe–O and Fe–Ti–O phases is best interpreted as advanced oxidative weathering coupled with density driven mineral concentration. The oxidation of sulfides to hematite and magnetite under intermittent O_2 exposure results in the formation of ferruginous concentrates Kądziołka-Gaweł et al. [21], while hydraulic sorting in low energy fluvial settings enriches dense Ti and Mn bearing phases (such as ilmenite and Mn oxides) [32]. Furthermore, such magnetite and hematite rich tailings have demonstrated suitability for magnetic separation and beneficiation processes, and can be utilized as iron-sand feedstock or construction aggregate precursors in studies of magnetic tailings and upgrading methods [24]. Consequently, ST2 is geochemically and mineralogically better suited than ST1 for iron recovery and material reuse, provided that follow up integrated characterization, pilot beneficiation, and environmental risk assessments are conducted [1].

ST1's chalcopyrite-like sulfide assemblage indicates clear potential for secondary copper recovery using hydrometallurgical routes validated for low-grade tailings, and microstructural liberation data are critical to assess amenability to such treatments Trifunović et al. [14]. ST2's enrichment in Fe–O and Fe–Ti–O phases (magnetite/hematite ± ilmenite) makes it a favorable feedstock for iron-sand beneficiation and civil-aggregate applications, consistent with magnetic tailings upgrading studies [33]. The observed secondary alteration and hydraulic sorting imply that an integrated flowsheet—combining physical separations (magnetic, gravity) with targeted chemical/hydrometallurgical extraction for Ti and residual Cu—will best balance recovery and environmental control, as recommended for heterogeneous tailings reprocessing [34]. Properly characterized and managed, differentiated treatment of ST1 and ST2 can enable sustainable metal recovery and reduced disposal impacts in Mimika [35].

3.4 Synthesis of Findings

Integrated mineralogical–geochemical–microstructural data demonstrate a clear ST1–ST2 differentiation: ST1 is a less altered, silicate dominated tailings horizon (silica/carbonate enrichment), whereas ST2 is an oxidized, ferruginous unit enriched in Fe–Ti oxides and heavy minerals (magnetite/hematite ± ilmenite), reflecting progressive sulfide→oxide transformation and density sorting [14], [1], [21], [24], [29]. These differences are driven by exposure time, fluctuating water levels and periodic air contact (redox cycling) and by hydrodynamic energy that concentrates dense phases in low energy zones [9], [32], [26], [25]. Consequences for reuse: ST1 is amenable to secondary Cu recovery via hydrometallurgical routes informed by microstructural liberation data, while ST2 is better suited to magnetic/gravity beneficiation for iron sand feedstock and Ti oxide recovery or aggregate use, provided AMD risk is managed and integrated physical–chemical extraction trials are applied [14], [3], [33], [34], [6], [10].

The Mimika ST1–ST2 differentiation and inferred oxidation/den¬sification pathways align with global tailings-management trends emphasizing characterization-led reuse and secondary recovery [10]. Case studies from Brazilian and Chilean copper and iron mining districts document analogous sulfide to oxide transformations and heavy-mineral concentration under fluctuating redox and hydrodynamic conditions, which inform recovery potential and acid mine drainage (AMD) risk management [25]. Practically, tailings from these regions have been reprocessed using flotation, hydrometallurgical leaching, and magnetic/gravity separation to recover copper, iron, and titanium (including titanomagnetite), and they have been repurposed in masonry and engineering materials—demonstrating viable circular-economy pathways that could be applied to Mimika, given integrated characterization techniques such as X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDS) along with pilot beneficiation trials [36]. Adoption of such targeted, governance-aligned programs, including AMD control alongside tailored physico-chemical extraction methods, would maximize resource recovery while mitigating environmental liabilities [10].

The insights from this study are significant for sustainable tailings management and resource recovery. The spatial differentiation between ST1 and ST2 indicates that tailored recovery strategies may be required depending on the degree of oxidation and mineral composition at each site. For instance, the relatively unaltered ST1 tailings, rich in chalcopyrite-like sulfides, may be more suited for copper recovery, while the more oxidized ST2 material, rich in iron oxides and titanium-bearing minerals, could be used for iron and titanium extraction or in industrial applications such as iron sand production and geopolymer raw materials. These findings support the growing global emphasis on recycling and reusing tailings as part of a circular economy, reducing the environmental footprint of mining activities while providing valuable resources for various industries.

4. Conclusion

The tailings from the Kali Kabur River in Mimika Regency are rich in Fe_2O_3, with dominant minerals including magnetite, ilmenite, diopside, and andradite. SEM–EDS analysis confirms the presence of chalcopyrite and pyrite, indicating that copper (Cu) may be a viable resource for extraction. The findings suggest that Mimika's tailings hold significant potential for reuse, both as iron sand feedstock and as secondary sources of Fe–Cu metals. This offers an opportunity for the development of sustainable mining practices that prioritize resource recovery. However, to fully harness the potential of these tailings, further studies are recommended to assess the economic and environmental feasibility of their extraction. These studies should focus on the costs and efficiency of various extraction techniques, such as flotation, leaching, or magnetic separation, as well as the potential environmental impacts of reprocessing the tailings, including the management of residual waste and the mitigation of contamination risks. The results from this study have important implications for local mining policies and sustainability practices in Mimika and other similar mining regions in Indonesia. By promoting the reutilization of mining waste, local industries can reduce their environmental footprint and create new economic opportunities through the recovery of valuable metals. Moreover, these findings can inform government regulations and initiatives aimed at encouraging sustainable mining practices, supporting a transition towards a circular economy in the mining sector. This approach can serve as a model for other mining areas in Indonesia, helping to balance industrial growth with environmental conservation and resource efficiency.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

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