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SEM-EDS Characterization of Metal-Bearing Particles in Kali Kabur River Sediments, Mimika, Central Papua, Indonesia: A Preliminary Mineralogical Assessment

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The Grasberg porphyry copper-gold mining district in Central Papua, Indonesia, has historically discharged tailings into the Ajkwa river system, raising concerns about downstream heavy-metal contamination in tributaries such as Kali Kabur, Mimika Regency. Because bulk geochemical techniques (e.g., XRD, XRF, ICP-MS) characterize average sediment composition but cannot resolve which specific mineral grains host which metals, this preliminary study applied Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS) spot analysis to two grab sediment samples from Kali Kabur (TS1, Lab No. 3647.25; TS2, Lab No. 3648.25), examined at the accredited tekMIRA laboratory (Certificate of Analysis No. 1044/LFM/10/2025) following internal method PU-3002FM. Backscattered electron imaging guided selection of eight metal-bearing particles (four per sample) for quantitative elemental analysis in weight percent. Results identified a Cu-Fe-S particle consistent with a chalcopyrite-like phase (TS1, Spectrum 1: Cu 44.78 wt%, Fe 22.58 wt%, S 32.64 wt%), a near-stoichiometric pyrite grain (TS1, Spectrum 2: S 47.19 wt%, Fe 52.81 wt%), iron oxide particles in both samples, quartz/silicate particles in both samples, and, in TS2, a Ti-Fe-Al-Si-O particle consistent with altered ilmenite/titanomagnetite intergrown with aluminosilicates, together with an Mn-bearing aluminosilicate phase. These assemblages are mineralogically consistent with the known porphyry Cu-Au mineralization and associated alteration facies of the Grasberg district. However, because no upstream or background reference samples, bulk metal concentrations, or independent mineralogical confirmation (e.g., XRD) were obtained, the data cannot, by themselves, distinguish natural geogenic inputs from mining-derived material, nor support quantitative statements about bioavailability or ecological/human health risk. The findings are reported as a preliminary, particle-level screening that complements but does not substitute for bulk geochemical and mineralogical characterization. We recommend that future work expand sample coverage with georeferenced, depth-controlled sampling and paired background sites, integrate SEM-EDS with XRD or automated mineralogy (e.g., QEMSCAN/MLA) and bulk ICP-MS/AAS analysis, and apply sequential extraction to evaluate bioavailable metal fractions before firm conclusions about environmental health risk in the Kali Kabur system can be drawn.

Keywords: Copper sulfide, Mimika Central Papua, Particle-level speciation, Sediment characterization, SEM-EDS

INTRODUCTION

The Grasberg mine, in the highlands of Mimika Regency, Central Papua Province, Indonesia, is one of the world's largest copper-gold deposits, operated by PT Freeport Indonesia (PT-FI). Its open-pit and underground operations have historically discharged tailings via riverine

disposal into the Ajkwa river system, which flows toward the lowlands near Timika and ultimately the Arafura Sea (Alonzo et al., 2016). This practice has been associated with substantial sediment aggradation, elevated suspended particulate matter, and reported increases in downstream heavy-metal concentrations, particularly

copper (Alonzo et al., 2016). Kali Kabur, a river in the Timika area, lies within this potentially affected watershed and receives sediment inputs that may originate from natural erosion of the highly mineralized porphyry system, from anthropogenic mining-related sources, or from a combination of both.

Previous mineralogical studies in Mimika provide useful regional context. X-ray diffraction (XRD) of black-sand deposits at the Amamapare estuary identified quartz, calcite, chlorite, sanidine, phlogopite, spinel, and magnetite as the dominant phases (Putri & Batloloni, 2022). X-ray fluorescence (XRF) analysis of Amamapare River sediments reported major oxide components including SiO₂, Al₂O₃, TiO₂, Fe₂O₃, MgO, CaO, Na₂O, K₂O, MnO, and P₂O₅ (Putri et al., 2023). Together, these studies establish a regional mineralogical and geochemical baseline for the watershed.

Despite this baseline, an analytical gap remains. Bulk techniques such as XRD and XRF describe the average mineralogical or elemental composition of a sample but cannot resolve which individual mineral grains host which metals, nor how metals are physically associated with co-existing phases. This distinction matters because metal bioavailability and mobility are governed largely by mineralogical form rather than by total concentration alone: copper hosted in a stable primary sulfide such as chalcopyrite behaves very differently under environmental weathering than copper sorbed onto oxide surfaces, held in carbonates, or present as free ions (Boer & Crosby, 1995; Gupta, 2023). Sulfides can oxidize under changing redox conditions, pH, or sediment resuspension, generating acidity and releasing metals in more mobile, potentially more toxic forms. SEM-EDS spot analysis addresses this gap by coupling high-resolution particle imaging with in-situ quantitative elemental microanalysis, enabling direct identification of discrete metal-bearing phases and their textural associations information that bulk XRD or XRF alone cannot provide (Boer & Crosby, 1995; Chen, 2017; Que et al., 2024). Automated variants such as Mineral Liberation Analysis (MLA) or QEMSCAN extend this approach to statistical mineral quantification and have been used successfully to partition metal(loid) contaminants among particulate phases in mining- and smelting-polluted soils (Tuhý et al., 2020), though manual spot analysis remains a practical, lower-cost option for targeted screening of metal-rich particles. To our knowledge, no previous study in the Kali Kabur/Amamapare watershed has applied particle-scale SEM-EDS characterization; prior regional work has relied exclusively on bulk XRD (Putri & Batloloni, 2022) and XRF (Putri et al., 2023) analyses. The present study is intended as a preliminary, exploratory application of SEM-EDS to this specific analytical gap rather than as a comprehensive contamination assessment.

Recent international studies continue to demonstrate the value of combining particle- or mineral-scale techniques with bulk geochemistry in mining-influenced river systems: examples include lead-zinc mining catchments in China, where combined XRD-EDS

analysis linked heavy-metal distribution to host-mineral identity across sediment size fractions (Que et al., 2024); zinc-smelting sites, where speciation was shown to depend on local geochemical drivers (He et al., 2024); wetland sediments affected by diffuse contamination (Kachoueian et al., 2024); lake-wetland systems in China (Wang, 2023); and artisanal small-scale gold-mining soils and sediments in Cameroon, where sequential extraction combined with SEM/EDS distinguished stable from bioavailable metal fractions (Danala Danga et al., 2025). These studies illustrate both the analytical value of particle- and phase-level characterization and the multi-method integration typically required before contamination or risk conclusions are drawn.

The broader geological and mineralogical context of mineralized systems in this part of Indonesia has also been documented elsewhere: fluid-inclusion studies at the Awak Mas gold prospect (Putri, 2024) and geochemical investigations of base-metal deposits in North Toraja (Pakombong & Putri, 2025) illustrate how mineralogical and geochemical data are used to reconstruct ore-forming processes and tectonic settings in Indonesian mineralized terranes, reinforcing the general principle that integrating mineralogical observation with geochemical interpretation is important when assessing sediment provenance in mining-influenced areas.

Understanding metal speciation in sediments of rivers such as Kali Kabur is relevant because local communities in Mimika Regency depend on riverine resources for fisheries, transportation, agriculture, and, in some cases, domestic water use. Elevated bioavailable copper and other metals can, in principle, affect aquatic biodiversity and enter the human food chain; sediment quality guidelines (e.g., NOAA, CCME) provide thresholds for total metals, and particle-level data of the kind generated here can, in future integrated studies, help refine interpretation of such thresholds.

This study presents a preliminary SEM-EDS characterization of metal-bearing particles in two sediment samples from Kali Kabur, analyzed at the accredited tekMIRA laboratory. The specific objectives were to: (1) identify, at the particle scale, the mineral phases hosting Cu, Fe, Ti, and Mn in these sediments; (2) evaluate the extent to which the particle-level data are consistent with the known mineralogy of the Grasberg porphyry Cu-Au system; and (3) critically discuss, with explicit acknowledgment of the study's methodological limitations, the implications of these preliminary findings for future environmental health research in the Kali Kabur system. This study does not attempt to attribute sediment contamination to mining versus natural sources, nor to quantify ecological or human health risk, because the data required for such determinations — bulk metal concentrations, background/reference sites, and bioavailability measurements — were not collected.

METHODS

Study Area and Sample Collection

Kali Kabur is situated in Mimika Regency, Central Papua, Indonesia, downstream of the Grasberg-Ertsberg mining district in the Sudirman Mountains. The river forms part of the broader Ajkwa riverine system, influenced by both natural sediment transport from mineralized catchments and historical tailings discharge.

As a first, exploratory application of particle-scale SEM-EDS to this specific river system, this study adopted a targeted, small-n screening design rather than a spatially representative sampling program. Two sediment samples were collected as grab samples from the river bed and submitted to the laboratory for analysis (Certificate of Analysis No. 1044/LFM/10/2025): Sample TS1 (Laboratory No. 3647.25), collected at -4.5421238, 136.9038604 (Plus Code 6Q7RFW53+5G), and Sample TS2 (Laboratory No. 3648.25), collected at -4.541692, 136.9035902 (Plus Code 6Q7RFW53+8C), approximately 57 m apart along the Kali Kabur channel. Coordinates were logged in the field with a GPS-enabled camera application at the time of collection. The two-sample design was intended to test the feasibility and analytical value of SEM-EDS spot characterization in this environment, not to characterize spatial variability in sediment mineralogy along the river. We treat this small sample size as the principal limitation of the study (see Study Limitations, below): with $n = 2$, the results cannot be generalized to the broader Kali Kabur system, and no statistical inference about spatial or compositional variability is possible.

Field photographs indicate an approximate sampling depth on the order of 10 cm below the sediment surface at the TS1 location; however, a fully standardized depth protocol (e.g., corer or scoop type, number and volume of sub-samples composited per station, sediment texture description at the point of collection) was not documented for either station and is not available for this manuscript. We flag this explicitly as a reproducibility limitation. Readers should treat the samples as shallow grab samples of near-surface river-bed material from the Kali Kabur channel within Mimika Regency, collected at the coordinates above but without a fully standardized depth or compositing protocol. Future sampling campaigns by our group will record sampling depth with a corer of known geometry, channel position (thalweg vs. bank), and a standardized composite-sampling protocol to allow full reproducibility.

SEM-EDS Analysis and Quality Assurance

Sample preparation and analysis were conducted at the Laboratory of Mineral, Balai Besar Pengujian Mineral dan Batubara (tekMIRA), Ministry of Energy and Mineral Resources, Bandung, Indonesia, an accredited facility (LP-641-IDN), using the laboratory's validated procedure PU-3002FM for SEM-EDS spot (point) analysis. Samples were dried, mounted on aluminum stubs using conductive adhesive, and coated with a thin carbon layer to ensure electrical conductivity and prevent charging under the electron beam. Analyses were performed using a scanning

electron microscope equipped with an energy-dispersive X-ray spectrometer (specific instrument model held in laboratory records).

Backscattered electron (BSE) imaging was used to locate particles with high mean atomic number (appearing bright), indicative of enrichment in heavy elements such as Cu, Fe, Ti, or Mn. Spot EDS analyses targeted these metal-bearing particles at magnifications of approximately 55–100 $\times$, corresponding to field widths of ~ 1 mm to 500 μ m. Multiple spectra (four per sample) were acquired from different particles or distinct domains within particles to capture compositional variability. Acquisition parameters included an appropriate accelerating voltage (typically 15–20 kV), beam current, and live time for adequate counting statistics. Quantitative results were reported as weight percent (wt%), normalized to 100%, with associated sigma (standard deviation) values reflecting measurement precision; elements below detection limits were not reported.

Quality assurance for these analyses relied on the laboratory's internal accreditation framework rather than on independent verification by the authors. tekMIRA's accreditation (LP-641-IDN) and its validated SOP (PU-3002FM) specify instrument calibration and standardization procedures, and the reported sigma values provide a measure of counting-statistics precision for each element. However, several QA/QC elements common in peer-reviewed SEM-EDS mineralogical studies were not independently verified for this manuscript: (i) certified reference material (CRM) analyses accompanying the sample batch were not reported in the Certificate of Analysis; (ii) duplicate or replicate spot analyses on the same particle, beyond the reported sigma values, were not performed; and (iii) the specific instrument model, detector type, and calibration standards were not disclosed in the laboratory documentation available to the authors. We report these as explicit limitations of the present dataset rather than omitting them.

Mineral Phase Identification

Mineral phase identification was performed by comparing measured elemental compositions and ratios with ideal stoichiometric compositions of common rock-forming and ore minerals (chalcopyrite CuFeS_2 : Cu 34.63%, Fe 30.43%, S 34.94%; pyrite FeS_2 : Fe 46.55%, S 53.45%; quartz SiO_2 : Si 46.75%, O 53.25%; ilmenite FeTiO_3 : Fe 36.81%, Ti 31.56%, O 31.63%; hematite Fe_2O_3 : Fe 69.94%, O 30.06%). Deviations from ideal stoichiometry were attributed to natural solid solution, surface alteration, analytical spot placement on heterogeneous domains, or matrix effects associated with rough, unpolished particle surfaces. All data were sourced directly from the official Certificate of Analysis issued by tekMIRA.

Because mineral identification here relies on comparing spot elemental ratios with ideal stoichiometry rather than on independent structural confirmation (e.g., XRD, Raman spectroscopy, or electron backscatter diffraction), phase assignments — particularly for solid-

solution phases or fine, intimately intergrown minerals — should be regarded as provisional pending structural verification. This is discussed further under Study Limitations.

RESULTS AND DISCUSSION

General Particle Characteristics

SEM imaging showed that both sediment samples consisted of poorly sorted, heterogeneous particle assemblages ranging in size from fine sand to gravel (tens of μm to $>1\text{ mm}$). Particle morphologies were predominantly angular to sub-rounded, consistent with relatively short transport distances or recent deposition in a high-energy fluvial environment. BSE imaging highlighted a subpopulation of bright, high-density particles enriched in heavy metals against a darker background of silicate and oxide matrix grains. No obvious biogenic structures or organic coatings were noted in the imaged fields. Because particle selection targeted bright BSE grains rather than a random or statistically representative population, these observations describe the metal-bearing subpopulation specifically and should not be read as a quantitative characterization of the bulk sediment mineralogy.

Sample TS1 (Laboratory No. 3647.25)

Four representative EDS spectra were acquired from distinct particles in TS1 (Table 1). Spectrum 1 yielded a ternary Cu-Fe-S composition ($\text{Cu } 44.78 \pm 0.18\text{ wt\%}$, $\text{Fe } 22.58 \pm 0.31\text{ wt\%}$, $\text{S } 32.64 \pm 0.32\text{ wt\%}$). Although the

Cu:Fe ratio is higher than ideal chalcopyrite, the assemblage is consistent with a copper-iron sulfide phase, plausibly chalcopyrite with local Cu enrichment from supergene alteration, intergrowth with bornite or chalcocite, or preferential excitation of Cu-rich domains during analysis. This composition is consistent with — though not proof of — derivation from primary ore minerals of the Grasberg porphyry system.

Spectrum 2 showed a near-stoichiometric pyrite composition ($\text{S } 47.19 \pm 0.02\text{ wt\%}$, $\text{Fe } 52.81 \pm 0.42\text{ wt\%}$), consistent with FeS_2 . The slight Fe excess relative to ideal pyrite may indicate minor pyrrhotite admixture or analytical bias. Pyrite is abundant in the Grasberg deposit and its alteration zones.

Spectrum 3 was dominated by Fe and O ($\text{Fe } 70.86 \pm 0.17\text{ wt\%}$, $\text{O } 29.14 \pm 0.07\text{ wt\%}$), consistent with an iron oxide phase such as magnetite (Fe_3O_4 , theoretical Fe $\sim 72.4\%$) or hematite (Fe_2O_3 , $\sim 69.9\%$ Fe); such phases commonly form as oxidation products of primary sulfides or occur as detrital grains from oxidized portions of the deposit. Spectrum 4 was essentially Si and O ($\text{Si } 41.51 \pm 0.29\text{ wt\%}$, $\text{O } 58.49 \pm 0.72\text{ wt\%}$), consistent with quartz or a SiO_2 -rich phase (ideal quartz Si 46.7% , O 53.3% ; the slightly elevated O may reflect surface hydration or minor undetected elements).

Table 1.

EDS spot analysis results (wt%) for Sample TS1 (Lab No. 3647.25)

Spectrum	Elements (Wt %)	Sigma	Inferred Phase
1	S 32.64 / Fe 22.58 / Cu 44.78	0.32 / 0.31 / 0.18	Cu-Fe sulfide (chalcopyrite-like)
2	S 47.19 / Fe 52.81	0.02 / 0.42	Pyrite (FeS_2)
3	O 29.14 / Fe 70.86	0.07 / 0.17	Iron oxide (magnetite/hematite)
4	O 58.49 / Si 41.51	0.72 / 0.29	Quartz / SiO_2 phase

Note: Totals normalized to 100 wt%. Data from Certificate of Analysis No. 1044/LFM/10/2025, tekMIRA. Phase names are interpretive assignments based on elemental ratios, not independently confirmed by XRD or an equivalent structural technique.

Sample TS2 (Laboratory No. 3648.25)

Four spectra were analyzed from TS2 (Table 2). Spectrum 1 again indicated a quartz/silicate phase ($\text{O } 58.55 \pm 0.87\text{ wt\%}$, $\text{Si } 41.45 \pm 0.42\text{ wt\%}$). Spectrum 2 was an Fe-oxide ($\text{O } 31.68 \pm 0.23\text{ wt\%}$, $\text{Fe } 68.32 \pm 0.51\text{ wt\%}$), similar to that observed in TS1.

Spectrum 3 displayed a more complex assemblage ($\text{O } 48.05 \pm 0.52\text{ wt\%}$, $\text{Ti } 21.78 \pm 0.03\text{ wt\%}$, $\text{Fe } 6.84 \pm 0.47\text{ wt\%}$, $\text{Al } 12.91 \pm 0.73\text{ wt\%}$, $\text{Si } 17.58 \pm 0.76\text{ wt\%}$), consistent with a Ti-Fe oxide (ilmenite or titanomagnetite) partially altered or intimately mixed with aluminosilicate clay minerals. Ideal ilmenite contains $\sim 31.6\%$ Ti and 36.8% Fe; the lower Fe and presence of Al-Si suggest either detrital ilmenite grains with clay coatings or

authigenic alteration products consistent with tropical weathering. Spectrum 4 showed high O ($71.39 \pm 0.52\text{ wt\%}$) with Al ($21.46 \pm 0.73\text{ wt\%}$), Si ($17.58 \pm 0.76\text{ wt\%}$), and detectable Mn, consistent with an Mn-bearing aluminosilicate — possibly Mn-substituted clay, feldspar, or a discrete Mn-oxide/hydroxide phase intermixed with the silicate matrix.

Table 2.

EDS spot analysis results (wt%) for Sample TS2 (Lab No. 3648.25)

Spectrum	Elements (Wt %)	Sigma	Inferred Phase
1	O 58.55 / Si 41.45	0.87 / 0.42	Quartz / silicate
2	O 31.68 / Fe 68.32	0.23 / 0.51	Iron oxide
3	O 48.05 / Ti 21.78 / Fe 6.84 / Al 12.91 / Si 17.58	0.52 / 0.03 / 0.47 / 0.73 / 0.76	Ti-Fe oxide + aluminosilicate (altered ilmenite/clay)
4	O 71.39 / Al 21.46 / Si 17.58 / Mn (detected)	0.52 / 0.73 / 0.76 / —	Mn-bearing aluminosilicate / clay

Note: Data extracted and summarized from Certificate of Analysis No. 1044/LFM/10/2025, tekMIRA. Minor elements may be present below reporting thresholds. Phase names are interpretive, based on elemental ratios; not independently confirmed by XRD.

The SEM-EDS results provide particle-level evidence of metal-bearing mineral phases in Kali Kabur sediments that are mineralogically consistent with the geology of the Grasberg district. The occurrence of quartz, iron oxides, Ti-bearing minerals, and aluminosilicate phases here parallels previous bulk mineralogical work in the Mimika region: XRD analyses of Amamapare estuary sediments reported abundant quartz and magnetite with chlorite and feldspar-group minerals (Putri & Batloloni, 2022), and XRF analyses of Amamapare River sediments documented elevated Fe₂O₃, TiO₂, and SiO₂, reflecting a comparable oxide-silicate mineral assemblage (Putri et al., 2023).

On source attribution. It is important to state clearly what these data can and cannot demonstrate regarding sediment provenance. The mineral assemblage identified here — chalcopyrite-like Cu-Fe sulfide, pyrite, iron oxides, quartz, a Ti-Fe oxide/aluminosilicate intergrowth, and an Mn-bearing aluminosilicate — is mineralogically consistent with derivation from the Grasberg porphyry Cu-Au system and its associated alteration facies. However, consistency with a geological source is not equivalent to source attribution. The Kali Kabur catchment drains naturally mineralized terrain independent of active mining, so sulfide- and oxide-bearing detritus could originate from natural erosion of the porphyry system, from historical or ongoing mining-related sediment transport, or from a mixture of both. Distinguishing these pathways would require, at minimum, comparative sampling from tributaries or reaches upstream of, or otherwise unconnected to, mining-influenced drainage, together with geochemical or isotopic provenance indicators (e.g., Pb isotope ratios, rare-earth element patterns) — none of which were available for this study. Accordingly, we describe the observed assemblage as consistent with the known porphyry mineralization of the district, which mining is also documented to have mobilized and redistributed downstream via tailings transport (Alonzo et al., 2016), rather than attributing it specifically to mining activity.

The Cu-Fe sulfide particle in TS1 (Spectrum 1) is noteworthy: its measured Cu content (44.78 wt%) exceeds the stoichiometric value for pure chalcopyrite (34.63 wt%), a deviation commonly observed in natural samples due to (i) supergene or hypogene enrichment producing Cu-rich rims or secondary covellite/digenite, a process documented using comparable SEM-BSE-EDS approaches in other porphyry Cu deposits (Yousefi Soorani et al., 2022), (ii) intimate intergrowths with other Cu sulfides, or (iii) geometric and matrix effects in SEM-EDS analysis of irregular, unpolished particles. The overall Cu-Fe-S signature is consistent with the primary copper mineralization style characteristic of the Grasberg porphyry Cu-Au deposit, where chalcopyrite is the dominant Cu-ore mineral accompanied by pyrite and bornite in potassic and phyllic alteration zones — though, as above, this consistency does not by itself establish that this particular grain derives from active mining rather than natural erosion of mineralized rock.

Pyrite identification in TS1 (Spectrum 2) is expected given its abundance in the orebody and wall rocks. Pyrite oxidation is a well-documented driver of acid mine drainage (AMD) in sulfide-rich environments ($\text{FeS}_2 + 15/4 \text{O}_2 + 7/2 \text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})_3 + 2 \text{SO}_4^{2-} + 4 \text{H}^+$; Yuan et al., 2022), and the resulting acidity can mobilize Cu²⁺, Fe²⁺/³⁺, and trace elements that may co-occur in the deposit. Similar concerns about the environmental behavior of metal-bearing minerals have been raised in previous Papua studies emphasizing that metal-rich sediments can act as secondary contamination sources through weathering and remobilization (Putri et al., 2023). At the same time, prior observations note that a portion of metals in this system remains in sulfide form with limited immediate bioavailability (Alonzo et al., 2016); the discrete sulfide particles identified here represent a potential — rather than a demonstrated — long-term metal source, contingent on oxidation during diagenesis, resuspension, or redox change at the sediment-water interface, a pathway by which particulate-bound metals have been

shown elsewhere to be released back into the water column (Liu et al., 2023).

Iron oxide particles (TS1 Spectrum 3; TS2 Spectrum 2) likely represent secondary minerals formed by oxidative weathering of primary sulfides, or detrital grains from oxidized caps of the deposit. Such phases can act either as sinks for metals (through sorption and co-precipitation) or, under reducing conditions, as secondary sources through re-release of previously sequestered metals. The Ti-Fe-Al-Si-O particle in TS2 (Spectrum 3) likely reflects detrital ilmenite or titanomagnetite grains from mafic to intermediate igneous rocks in the catchment, with possible clay-mineral overgrowth or partial alteration under tropical weathering; ilmenite is a common, generally stable heavy mineral in fluvial and coastal placer sediments and is considered to pose low environmental risk, consistent with its recognized durability during weathering and transport (Chakraborty & Saha, 2021). The Mn-bearing aluminosilicate in Spectrum 4 may reflect detrital Mn-oxide/hydroxide (common in lateritic soils of Papua) or Mn substitution in clay lattices; Mn concentrations here appear minor, though Mn is recognized as both an essential nutrient and, at elevated exposure, a neurotoxin (Pajarillo et al., 2022).

Comparison with Recent International Studies (2020–2025).

These findings can be contextualized against recent international work on mining-impacted sediments. Combined XRD-EDS characterization in a lead-zinc mining catchment in Hunan Province, China, showed that fine-grained secondary clay minerals (chlorite, illite) preferentially concentrate heavy metals such as Cd, Pb, and As relative to coarser primary mineral fractions, and that metal speciation depended strongly on host-mineral identity (galena, sphalerite, pyrite) rather than particle size alone (Que et al., 2024) — broadly consistent with the sulfide-hosted Cu-Fe assemblage identified in TS1. Sequential-extraction and SEM/EDS-based speciation work on artisanal small-scale gold-mining soils and sediments in Cameroon found that potentially toxic elements were predominantly held in more stable, less bioavailable geochemical fractions under ambient conditions, underscoring that mineralogical identification alone — without paired sequential extraction or bulk analysis — is insufficient to establish bioavailability or risk (Danala Danga et al., 2025).

Wetland- and lake-sediment studies from Iran and China similarly emphasize that mineral speciation, not total metal concentration, is a primary determinant of ecological risk, and that source apportionment requires multivariate or isotopic evidence beyond mineralogical description alone (He et al., 2024; Kachoueian et al., 2024; Wang, 2023). A directly analogous case is the Ok Tedi/Fly River system in Papua New Guinea, another porphyry Cu-Au mine using riverine tailings disposal, where a decade of paired copper concentration and toxicity monitoring data enabled a full probabilistic risk assessment distinguishing chronic-effect risk by distance from the mine and by

hydrological period (Spadaro et al., 2022) — precisely the kind of longitudinal, quantitative dataset that remains to be built for Kali Kabur before comparable risk conclusions can be drawn. Taken together, this recent literature supports both the analytical value of the particle-scale characterization demonstrated here and the need for the multi-method integration — bulk chemistry, sequential extraction, and comparative/background sampling — that the present preliminary dataset lacks.

On environmental health implications.

Because bulk Cu concentrations, bioavailability, and background conditions were not measured in this study, any discussion of environmental health implications must be treated as provisional context rather than a risk assessment. With that caveat, the presence of Cu-sulfide and pyrite particles is, in principle, relevant to a river system supporting local livelihoods: copper is toxic to aquatic organisms at elevated bioavailable concentrations, with documented mechanisms including disruption of ion-regulatory function and oxidative stress in fish gills, liver, and kidney (Liao et al., 2023), and sediment Cu concentrations exceeding Probable Effect Levels (PEL ~149 mg/kg dry weight; MacDonald et al., 2000) have been associated with adverse biological effects elsewhere. We cite this threshold only to illustrate the kind of bulk data that would be needed to evaluate risk in Kali Kabur — no such bulk measurement was made here, and the PEL value should not be read as implying that Kali Kabur sediments approach or exceed it. Because metals can be concentrated in discrete particles, even moderate bulk levels could in principle mask localized hotspots with elevated bioavailability upon oxidation or ingestion by deposit-feeding organisms; fine-grained sulfide particles are generally more mobile and reactive than coarser grains.

Potential human exposure pathways in Mimika could include consumption of fish and shellfish from the river and estuary — an exposure route for which quantitative human health risk assessment frameworks (e.g., target hazard quotient, estimated daily intake) exist and have been applied to metals in seafood elsewhere (Tanhan et al., 2022), though not in this study — incidental ingestion or dermal contact with sediment during fishing or agricultural activities, and use of river water for irrigation or domestic purposes (drinking water is typically sourced elsewhere); chronic low-level Cu exposure has, in other settings, been linked to gastrointestinal, hepatic, renal, and neurological effects, with children considered more vulnerable. We emphasize that none of these pathway-level statements have been evaluated with data from this study; they are presented as motivation for the integrated follow-up work outlined below, not as findings of this study.

This study has several limitations that should guide how its findings are interpreted. (1) Sample size: only two sediment samples (n=2, four spectra each) were analyzed, which is insufficient to represent the spatial or compositional variability of the Kali Kabur system; the

results describe these two samples only. (2) Non-random particle selection: spot analyses targeted bright BSE particles rather than a statistically representative population, biasing the dataset toward metal-rich grains and precluding quantitative statements about bulk mineral abundance. (3) No automated mapping or statistical mineral quantification (e.g., MLA, QEMSCAN) was performed. (4) No complementary bulk chemistry (ICP-MS, AAS) or sequential extraction data were available, so bioavailable metal fractions and total sediment metal loads remain unknown. (5) No independent structural confirmation (e.g., XRD, Raman, EBSD) of the SEM-EDS-inferred mineral phases was obtained; phase assignments are therefore provisional. (6) No background or reference sites (e.g., tributaries unconnected to mining-influenced drainage) were sampled, so natural versus mining-derived sources cannot be distinguished. (7) Sampling metadata remain partly limited: GPS coordinates for both stations are available (see Study Area and Sample Collection), but a fully standardized depth protocol and documented compositing procedure were not recorded. (8) CRM-based QA/QC and replicate analyses beyond the reported sigma values were not documented for this sample batch.

Future research should address these gaps directly: expanding spatial and temporal sample coverage with georeferenced, depth-controlled sampling and documented QA/QC; including background/reference sites; integrating SEM-EDS with automated mineralogy (MLA/QEMSCAN; Tuhý et al., 2020) or XRD for independent phase confirmation; coupling with bulk ICP-MS analysis and selective sequential extraction (e.g., BCR or Tessier schemes, with attention to the documented sensitivity of availability estimates to the extraction procedure chosen; Cuvier et al., 2021) to quantify mobile metal fractions; and applying ecological risk assessment frameworks (e.g., the Sediment Quality Triad; Suter & Cormier, 2011) alongside human health risk assessment models. Collaboration among mining operators, government agencies (Ministry of Environment and Forestry, ESDM), local health authorities, and indigenous communities would support transparent, adaptive monitoring as this integrated evidence base develops.

CONCLUSION

SEM-EDS spot analysis of two grab sediment samples from Kali Kabur, Mimika, Central Papua, provides a preliminary, particle-level characterization of metal-bearing phases, including a chalcopyrite-like Cu-Fe sulfide, pyrite, iron oxides, quartz/silicates, a Ti-Fe oxide intergrown with aluminosilicates, and an Mn-bearing aluminosilicate. This mineral assemblage is mineralogically consistent with the known porphyry Cu-Au mineralization and alteration facies of the Grasberg district. However, because no background/reference sediments, bulk metal concentration data, or independent mineralogical confirmation were obtained in this study, these findings cannot, on their own, distinguish natural geogenic inputs from mining-derived material, nor support quantitative conclusions about bioavailability or ecological/human

health risk. The results are best interpreted as evidence that particle-scale SEM-EDS analysis is a feasible and informative complement to bulk geochemical techniques in this setting, rather than as a stand-alone contamination assessment. We recommend that future studies in the Kali Kabur system expand sample coverage with georeferenced and depth-controlled sampling, include upstream or non-mining-influenced background sites, and pair SEM-EDS with bulk ICP-MS/AAS analysis, XRD or automated mineralogy, and sequential extraction to more rigorously evaluate source attribution, metal bioavailability, and environmental health implications.

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