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Integrated GCA–XRF characterization of REE-associated mineral enrichment in tin-processing residues from Bangka Island, Indonesia

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ABSTRACT

This study aims to characterize REE-associated mineral enrichment in tin-processing materials from Bangka Island, Indonesia, using integrated mineralogical and geochemical evidence. Mining-front material, mine tailings, and processing residues were prepared at comparable particle-size fractions and analyzed using Grain Counting Analysis (GCA) and X-Ray Fluorescence (XRF). Monazite increased from not detected in mining-front material to 1.18% in tailings and 6.14% in processing residues, while zircon increased to 0.25% and 4.26%, respectively. Processing residues contained the highest Y (9,510 ppm), Zr (1.209%), Nb (2,040 ppm), and Th (1,031 ppm) concentrations. The consistent mineralogical and geochemical trends indicate enrichment of REE-associated accessory minerals in processing residues. However, mineral-specific REE quantification, liberation, recovery, and economic assessments are required before these residues can be considered viable secondary REE resources.

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Introduction

Rare Earth Elements (REE) have become strategically important because of their essential roles in permanent magnets, electronics, electric vehicles, renewable-energy systems, and other advanced technologies (Balaram, 2019; International Energy Agency [IEA], 2024). Growing demand and geographically concentrated supply chains have increased interest in identifying alternative and secondary sources of these elements. Indonesia has considerable potential in this context because tin mineralization in Bangka-Belitung occurs within the Southeast Asian Tin Belt, a major metallogenic province associated with recurrent granitic magmatism and extensive placer development (Aditya et al., 2020; Sun et al., 2025). Weathering and erosion of tin-bearing rocks, followed by sedimentary transport and density-controlled sorting, can produce assemblages containing cassiterite and resistant heavy accessory minerals. Studies in Bangka-Belitung have identified monazite and other REE-associated minerals within cassiterite-bearing systems, indicating that materials generated during tin mining and processing warrant investigation beyond their conventional value as sources of tin (Syafrizal et al., 2024).

Tin-processing residues are particularly relevant because beneficiation does not necessarily recover all economically or geochemically significant mineral phases. Differences in mineral density, grain size, morphology, and physical separation behavior can redistribute heavy accessory minerals among concentrates, tailings, and subsequent processing residues. Previous investigations have demonstrated that post-processing tailings from Bangka may contain critical-mineral components that remain after primary tin recovery (Zglinicki et al., 2021). Similar evidence from Indonesian tin-mining environments indicates that residual materials can retain REE-bearing minerals and associated elemental signatures (Irzon, 2021; Qurratu'ain et al., 2023). Consequently, evaluating these materials solely on the basis of residual cassiterite may underestimate their mineralogical significance. Understanding how accessory-mineral abundance changes through successive processing stages is therefore important for determining whether beneficiation produces systematic enrichment of mineral phases associated with REE and other critical elements (Frutuoso et al., 2026; She et al., 2021; Varrica & Alaimo, 2024; Zafar et al., 2025).

Mineralogical and geochemical characterization provides complementary information for evaluating such enrichment. Grain Counting Analysis (GCA) can identify mineral assemblages and estimate their relative abundance, but its effectiveness depends on grain size, counting representativeness, and the ability to distinguish accessory minerals microscopically (Schönig, 2024). X-Ray Fluorescence (XRF), in contrast, provides quantitative elemental information but cannot independently determine the specific mineral phases hosting individual elements (Oyedotun, 2018). Qurratu'ain et al. (2023) applied mineralogical and elemental approaches to investigate rare-earth-element occurrence in tin-mining tailings, demonstrating the relevance of combining complementary analytical evidence. Nevertheless, correspondence between changes in accessory-mineral abundance and elemental enrichment across successive materials from the mining front to later processing residues remains insufficiently characterized, particularly at individual tin-mining sites in Bangka.

This limitation is particularly relevant at the Front Penambangan Desa Bukit Layang, Kecamatan Bakam, Kabupaten Bangka, where site-specific evidence regarding the redistribution of accessory minerals through processing remains limited. Mineral assemblages and elemental concentrations cannot be assumed to be uniform among tin deposits because they are influenced by source-rock composition, weathering history, sedimentary sorting, and processing conditions (Aditya et al., 2020; Syafrizal et al., 2024). Moreover, the detection of elements such as Y, Zr, Nb, and Th should not automatically be interpreted as direct evidence that these elements are hosted by a particular REE-bearing mineral. Monazite and xenotime have distinct mineralogical and geochemical characteristics, whereas zircon may incorporate various trace elements through substitution within its crystal structure (Chong et al., 2024). Establishing correspondence between observable mineral enrichment and associated elemental signatures is therefore necessary before stronger interpretations of secondary-resource potential can be made (Fawzy et al., 2020; Ishanka et al., 2026; Kumar et al., 2023; Popelka-Filcoff et al., 2012).

The research gap addressed in this study lies in tracing mineralogical and geochemical changes across successive tin-mining and processing materials within the same site rather than characterizing tailings as an isolated end product. Previous studies have established the occurrence of REE-associated minerals in Bangka-Belitung and demonstrated the potential significance of post-processing materials (Syafrizal et al., 2024; Zglinicki et al., 2021). However, less attention has been given to whether changes from mining-front material to mine tailings and processing residues exhibit consistent correspondence between accessory-mineral abundance and associated elemental concentrations. Addressing this gap provides a more process-oriented understanding of mineral redistribution and avoids interpreting elemental enrichment independently from mineralogical evidence. The novelty of the present study therefore lies not merely in applying GCA and XRF, but in integrating their outputs comparatively across three successive material groups to identify systematic mineralogical–geochemical enrichment patterns.

Accordingly, this study aims to characterize REE-associated accessory-mineral enrichment in mining-front material, mine tailings, and processing residues from Desa Bukit Layang, Bangka, using integrated GCA and XRF evidence. GCA is employed to determine changes in mineral assemblages and relative abundance, while XRF is used to evaluate corresponding variations in elemental composition, particularly Y, Zr, Nb, and Th as geochemical indicators associated with heavy accessory-mineral assemblages (Balaram, 2019; Oyedotun, 2018). Rather than assuming that these elemental signatures directly identify specific REE-bearing mineral hosts, the study evaluates whether their concentration patterns correspond with observed changes in accessory-mineral abundance. This integrated approach provides a site-specific baseline for assessing mineral enrichment in tin-processing residues while maintaining a clear distinction between preliminary secondary-resource potential and evidence required to establish economically recoverable REE resources.

Method

This study employed a quantitative descriptive-comparative design to characterize mineralogical and elemental variations across successive materials generated during tin mining and processing. The study was conducted from January to April 2026 at the Front Penambangan Desa Bukit Layang, Kecamatan Bakam, Kabupaten Bangka, Kepulauan Bangka Belitung, Indonesia, within the operational area of PT Timah Tbk. Three material groups were purposively selected to represent the processing sequence: mining-front material collected from the tin-bearing layer before processing, mine tailings remaining after tin separation, and processing residues generated after the subsequent processing stage. Field observations and sampling were conducted using comparable procedures for each material group to enable direct assessment of mineral redistribution and relative enrichment across the processing sequence.

All collected materials were dried and separated according to particle size using a sieve shaker, and the mass of each fraction was recorded. The 70- and 100-mesh fractions were selected for subsequent analyses because they represented the dominant fractions used consistently across the three material groups. Mineralogical characterization was performed using Grain Counting Analysis (GCA) with a binocular microscope. Mineral grains were identified according to observable physical and optical characteristics, including color, luster, grain shape, relief, and transparency, and were subsequently counted by mineral species to determine their relative abundance. The same identification and counting procedures were applied to all samples. Geochemical characterization was performed using X-Ray Fluorescence (XRF) on corresponding prepared fractions to determine major, minor, and trace elemental concentrations, with particular attention to Y, Zr, Nb, and Th as indicators associated with heavy accessory-mineral assemblages.

Data analysis integrated the GCA and XRF results through descriptive and comparative evaluation across the mining-front material, mine tailings, and processing residues. Mineral abundance obtained from GCA was expressed as the percentage of counted grains for each identified mineral species, whereas elemental concentrations obtained from XRF were tabulated using consistent parameters across the three material groups. The integrated analysis examined whether increases in monazite, zircon, and other heavy accessory minerals corresponded with increasing concentrations of Y, Zr, Nb, and Th through the processing sequence. Elemental enrichment was interpreted as geochemical evidence associated with changes in mineral assemblages rather than direct confirmation of specific mineral hosts. No inferential statistical testing was applied because the analysis was designed to establish descriptive mineralogical geochemical patterns and provide a preliminary characterization of enrichment in tin-processing residues.

Results and Discussions

The mineralogical and geochemical results obtained from the Front Penambangan Desa Bukit Layang, Kecamatan Bakam, Kabupaten Bangka demonstrated a systematic change in mineral composition and elemental concentration across the mining-front material, mine tailings, and processing residues. These changes are relevant for evaluating the occurrence of accessory minerals potentially associated with Rare Earth Elements (REE). Grain Counting Analysis (GCA) identified cassiterite, ilmenite, quartz, monazite, zircon, tourmaline, and other accessory minerals, while X-Ray Fluorescence (XRF) provided the corresponding elemental composition. The integrated interpretation was used to determine whether the mineralogical changes were accompanied by enrichment of REE-associated elements. This approach is particularly relevant because GCA provides information on mineral identity and abundance, whereas XRF provides quantitative information on elemental composition.

The particle-size distribution showed that the three material groups were dominated by medium-to-fine fractions. The 70-mesh fraction represented 8.5 g in the mining-front material, 10.5 g in the tailings, and 17.6 g in the processing residues, while the 100-mesh fraction represented 7.8, 8.6, and 16.2 g, respectively. Because these fractions represented the dominant size range, the 70- and 100-mesh fractions were selected for GCA and XRF analyses. The selection was therefore intended to improve the representativeness of the mineralogical and geochemical characterization rather than to focus on an arbitrary particle-size class.

Table 1. Mineralogical composition of tin-bearing materials based on Grain Counting Analysis

Mineral	Mining Front (%)	Mine Tailings (%)	Processing Residues (%)
Cassiterite	5.11	1.58	2.21
Ilmenite	11.81	72.77	73.38
Monazite	0.00	1.18	6.14
Zircon	0.00	0.25	4.26
Quartz	79.38	23.67	13.90
Tourmaline	3.71	0.58	0.00
Limonite	0.13	0.00	0.13
Other minerals	Minor	Minor	Minor

The GCA results revealed a pronounced shift in mineral composition from the mining front to the processing residues. The mining-front material was strongly dominated by quartz at 79.38%, followed by ilmenite at 11.81%

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and cassiterite at 5.11%. Neither monazite nor zircon was identified in the counted grains from the mining-front sample. This does not necessarily demonstrate their complete absence from the deposit because accessory minerals occurring at very low abundance or as very fine grains may not be captured by microscopic grain counting. The occurrence of 3.83% UC/MIC in the mining-front sample also indicates that the material still represented a relatively heterogeneous mixture of valuable minerals and gangue before beneficiation.

After processing, the mineral assemblage changed substantially. In the tailings, ilmenite became the dominant mineral at 72.77%, whereas quartz decreased to 23.67% and cassiterite decreased to 1.58%. More importantly for the objective of this study, monazite and zircon became detectable at 1.18% and 0.25%, respectively. This change indicates that the beneficiation process preferentially removed part of the lighter or targeted mineral fraction while leaving a larger proportion of heavy accessory minerals in the residual material. The result agrees with the geological interpretation of placer tin deposits, in which mineral concentration is strongly controlled by differences in density and resistance to weathering. The most distinctive mineralogical enrichment occurred in the processing residues. Ilmenite remained dominant at 73.38%, while quartz declined further to 13.90%. Monazite increased to 6.14% and zircon to 4.26%, whereas cassiterite represented only 2.21%. The combined abundance of monazite and zircon therefore reached 10.40% in the processing residues, compared with 1.43% in the tailings and 0% in the mining-front sample. This pattern indicates that the residual material became progressively enriched in heavy accessory minerals during processing. The finding is important because monazite and zircon are recognized as accessory minerals associated with tin deposits and may host or be associated with REE and other critical elements.

The progressive increase in monazite and zircon is consistent with the regional geological setting of Bangka. The study area forms part of the Southeast Asian Tin Belt, where weathering of tin-bearing granitic rocks and subsequent sedimentary sorting can concentrate resistant heavy minerals in placer deposits. Sun et al. (2025) described the Southeast Asian Tin Belt as a long-lived tin-mineralization province associated with recurrent granitic magmatism, whereas Syafrizal et al. (2024) documented REE-bearing accessory minerals in cassiterite-associated materials from Bangka-Belitung. Thus, the enrichment observed in the present study is geologically plausible and provides site-specific evidence that processing residues may retain accessory mineral components that are not recovered as the principal tin product.

Table 2. Elemental composition of samples based on X-Ray Fluorescence analysis

Element	Mining Front	Mine Tailings	Processing Residues
Si	25.66%	22.34%	4.99%
Sn	3.583%	1.290%	1.341%
Ti	1.333%	3.905%	25.10%
Fe	1.232%	1.784%	17.26%
Zr	3,239 ppm	9,429 ppm	1.209%
Y	519 ppm	1,696 ppm	9,510 ppm
Nb	151 ppm	446 ppm	2,040 ppm
Th	68 ppm	80 ppm	1,031 ppm
U	16 ppm	33 ppm	160 ppm

The XRF results supported the mineralogical changes observed through GCA. The mining-front sample contained the highest Si concentration at 25.66%, consistent with its high quartz abundance of 79.38%. Tin was also relatively high at 3.583%, corresponding to the presence of 5.11% cassiterite. In contrast, Zr, Y, Nb, and Th were present at lower concentrations of 3,239 ppm, 519 ppm, 151 ppm, and 68 ppm, respectively. Although monazite and zircon were not identified microscopically in this sample, the detection of these elements indicates that accessory mineral components may occur below the detection or counting capability of the applied mineralogical procedure. The tailings exhibited a different geochemical signature. Si decreased to 22.34%, while Ti and Fe increased to 3.905% and 1.784%, respectively. This pattern is consistent with the increase in ilmenite identified by GCA, which reached 72.77%. At the same time, the concentrations of Zr, Y, Nb, and Th increased to 9,429 ppm, 1,696 ppm, 446 ppm, and 80 ppm. Thus, the geochemical results indicate that the tailings were enriched in heavy-mineral-associated elements relative to the mining-front material. The agreement between the increased heavy-mineral fraction and the elevated elemental concentrations strengthens the interpretation that beneficiation altered the distribution of accessory minerals rather than simply reducing the overall mineral content.

The processing residues displayed the strongest geochemical enrichment. Ti reached 25.10% and Fe 17.26%, corresponding to the dominant ilmenite content of 73.38%. Meanwhile, Si declined to only 4.99%, consistent with the reduction of quartz to 13.90%. More relevant to the study objective, Y increased to 9,510 ppm, Zr to 1.209%, Nb to 2,040 ppm, Th to 1,031 ppm, and U to 160 ppm. These were the highest concentrations among the three materials. The simultaneous increase in monazite and zircon identified by GCA and the increase in Y, Zr, Nb, and Th measured by XRF provide complementary evidence of heavy-mineral and REE-associated elemental enrichment in the processing residues.

Table 3. Integrated interpretation of mineralogical and geochemical indicators

Material	Main Mineralogical Indicator	Main Geochemical Indicator	Interpretation
Mining front	Quartz 79.38%; cassiterite 5.11%; monazite and zircon not detected	Y 519 ppm; Zr 3,239 ppm; Nb 151 ppm; Th 68 ppm	Initial placer material with low visible abundance of REE-bearing accessory minerals
Mine tailings	Ilmenite 72.77%; monazite 1.18%; zircon 0.25%	Y 1,696 ppm; Zr 9,429 ppm; Nb 446 ppm; Th 80 ppm	Enrichment of heavy minerals and associated elements after beneficiation
Processing residues	Ilmenite 73.38%; monazite 6.14%; zircon 4.26%	Y 9,510 ppm; Zr 1.209%; Nb 2,040 ppm; Th 1,031 ppm	Strongest mineralogical and geochemical indication of REE-associated enrichment

The integrated results answer the central research question concerning the relationship between mineral abundance and elemental composition. A clear correspondence was observed: the increase in monazite and zircon from the mining front through the tailings to the processing residues was accompanied by increasing concentrations of Y, Zr, Nb, and Th. Monazite is particularly relevant because it is a principal carrier of light REE, whereas zircon can contain REE as minor or substituting elements. The present results are therefore consistent with the use of combined mineralogical and geochemical evidence to strengthen interpretation of REE-bearing mineral systems (Chong et al., 2024).

An important finding is that the absence of visible monazite and zircon in the mining-front GCA sample did not correspond to an absence of REE-associated elemental signals. XRF still detected Y, Zr, Nb, and Th in that material. This discrepancy illustrates a methodological limitation of microscopic grain counting: accessory minerals may occur at concentrations or grain sizes that are difficult to observe through conventional counting. Consequently, the XRF signal should not be interpreted as direct proof of a specific mineral phase unless mineralogical evidence supports that association. Instead, the results provide a reasonable indication of mineralogical-geochemical association that requires confirmation through more mineral-specific analytical techniques. The same methodological consideration explains why the integration of GCA and XRF is more informative than either method considered independently. The processing residues showed the strongest overall potential within the materials investigated. Monazite increased from 0% in the mining-front sample to 1.18% in the tailings and 6.14% in the processing residues, while zircon increased from 0% to 0.25% and 4.26%. At the same time, Y increased from 519 ppm to 1,696 ppm and then to 9,510 ppm; Nb increased from 151 to 446 and 2,040 ppm; and Th increased from 68 to 80 and 1,031 ppm. The consistency of these trends suggests that mineral processing resulted in the relative concentration of heavy accessory minerals within the residual material.

The result has practical implications for mineral-resource management. The processing residue should not be regarded solely as a residual material from which the primary tin product has already been recovered. Within the investigated samples, it contained the highest concentration of the identified REE-bearing accessory minerals and the highest concentrations of several associated elements. Syafrizal et al. (2024) similarly reported the occurrence and potential significance of REE-bearing accessory minerals associated with tin deposits in Bangka-Belitung. However, the present results should be interpreted as evidence of potential, rather than proof of an economically recoverable REE resource. Economic viability depends on mineral liberation, recoverability, tonnage, processing performance, and the concentration of individual REE. The findings also indicate that beneficiation has a dual effect: it reduces the relative abundance of quartz and cassiterite while increasing the relative concentration of heavy accessory minerals in residual streams. Quartz declined from 79.38% in the mining-front material to 23.67% in tailings and 13.90% in processing residues. Conversely, ilmenite increased from 11.81% to 72.77% and 73.38%. This pattern demonstrates that the observed enrichment is closely related to the physical separation behavior of minerals during processing. Therefore, the elevated REE-associated elemental concentrations should be understood in the context of mineral concentration and redistribution rather than interpreted as newly generated REE during beneficiation.

The principal contribution of the study is consequently the identification of a consistent mineralogical-geochemical trend at the Front Penambangan Desa Bukit Layang, Kecamatan Bakam, Kabupaten Bangka: processing residues contained the strongest combined evidence of REE-associated mineral enrichment. The integration of GCA and XRF enabled the study to connect the observed abundance of monazite and zircon with corresponding enrichment in Y, Zr, Nb, and Th. This provides a site-specific baseline for evaluating the secondary-resource potential of tin-processing residues and extends previous studies that have primarily focused either on mineralogical composition or on elemental occurrence. Several limitations should nevertheless be acknowledged. GCA provides mineral identification and relative abundance but is constrained by grain size, counting representativeness, and the ability to recognize accessory minerals at low abundance. XRF provides elemental concentrations but does not, by itself, conclusively establish the mineral host of each element. Furthermore, the present study did not quantify individual REE species, determine mineral liberation, assess metallurgical recovery, estimate resources or reserves, or evaluate economic feasibility. The interpretation therefore remains a characterization and preliminary potential assessment rather than a resource evaluation. The research document accordingly recommends subsequent analyses using scanning electron microscopy–energy-dispersive spectroscopy, X-ray diffraction, and inductively coupled plasma mass spectrometry to obtain more precise mineral identification and individual REE quantification.

Future research should therefore extend sampling to additional locations and stratigraphic layers within the mining area, followed by mineral-specific and highly sensitive geochemical analyses. Particular attention should be directed toward confirming the hosts of Y, Nb, Th, and other critical elements and determining whether the elevated concentrations are controlled primarily by monazite, xenotime, zircon, or other accessory phases. Recovery testing and economic assessment would then be required to establish whether the processing residues identified in this study can realistically be developed as a secondary source of REE. In this way, the present study functions as a baseline characterization rather than an overextended claim of economic recoverability.

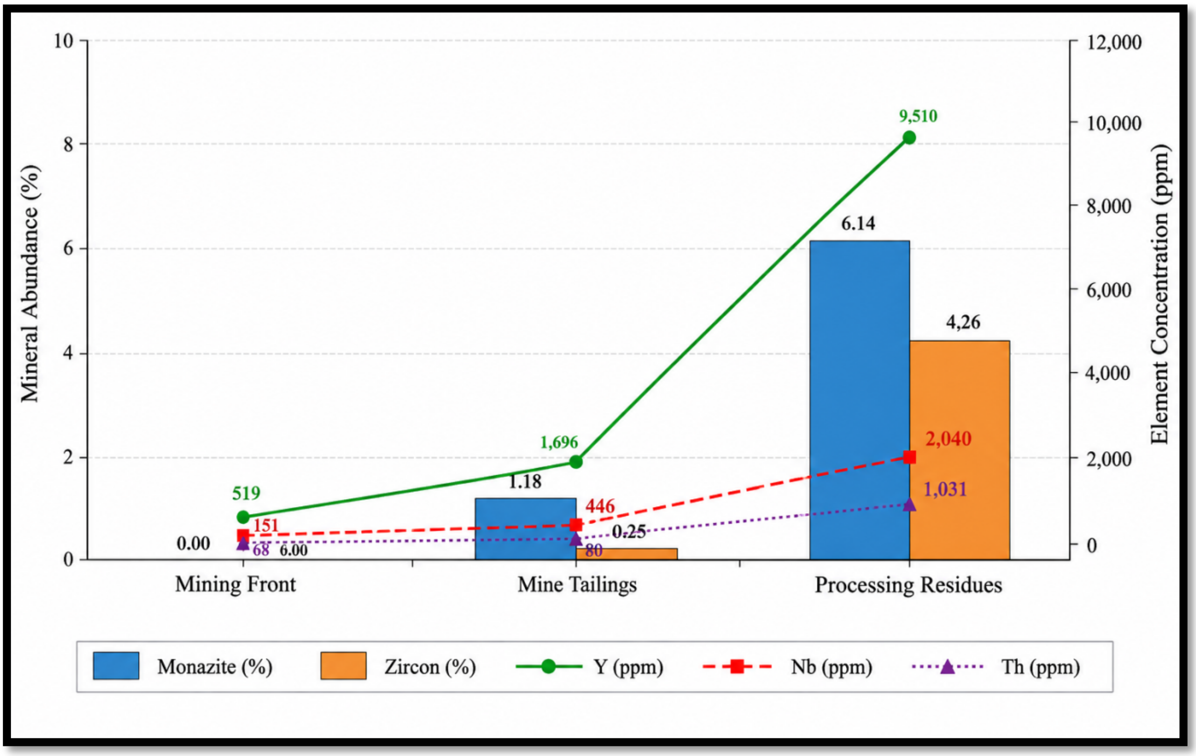

Figure 1. Comparison of REE-Associated Mineral Abundance and Elemental Enrichment Across Mining and Processing Materials

The mineralogical results demonstrate a systematic redistribution of heavy accessory minerals throughout the tin-processing sequence. Mining-front material was dominated by quartz (79.38%), whereas ilmenite increased markedly from 11.81% in the mining-front material to 72.77% in mine tailings and 73.38% in processing residues. More importantly, monazite increased from not detected in the mining-front material to 1.18% in tailings and 6.14% in processing residues, while zircon increased from not detected to 0.25% and 4.26%, respectively. This pattern indicates that beneficiation progressively reduced the relative proportion of quartz while concentrating denser and more resistant accessory minerals within the residual streams. Such redistribution is consistent with the mineralogical characteristics of placer tin systems, in which density contrasts and physical separation processes influence the accumulation of cassiterite-associated heavy minerals. Previous investigations in Bangka-Belitung have similarly identified monazite and other accessory minerals within cassiterite-associated materials, supporting the interpretation that tin-processing residues can preserve mineral fractions of potential critical-mineral significance (Abaka-Wood et al., 2022; Li et al., 2025; Paludo et al., 2018; Saleh et al., 2019).

The XRF results provide complementary geochemical evidence for this mineralogical enrichment. Y increased from 519 ppm in the mining-front material to 1,696 ppm in tailings and 9,510 ppm in processing residues, while Nb increased from 151 to 446 and 2,040 ppm and Th from 68 to 80 and 1,031 ppm, respectively. Zr also increased substantially, reaching 1.209% in processing residues. These trends indicate that the redistribution of heavy accessory minerals was accompanied by systematic enrichment of associated elemental signatures. The elevated Y concentration is particularly relevant because Y is commonly associated with HREE-bearing mineral systems, whereas increased Zr corresponds with the greater abundance of zircon observed through GCA. Nevertheless, Zr, Nb, and Th should not themselves be interpreted as direct measures of total REE concentrations, and their occurrence cannot independently establish a specific mineral host. Previous studies of Indonesian tin residues have likewise demonstrated that tailings can retain substantial concentrations of REE and associated critical elements after primary tin recovery (Cavalheiro et al., 2026; Malainine et al., 2022; Ünal-Kartal et al., 2026; Wang et al., 2019).

The correspondence between GCA and XRF results represents an important aspect of the present findings because neither technique alone provides sufficient evidence to establish mineralogical–geochemical relationships. The absence of microscopically detected monazite and zircon in the mining-front material, despite measurable concentrations of Y, Zr, Nb, and Th, illustrates this analytical distinction. Accessory minerals occurring at low abundance, within very fine fractions, or outside the counted grains may remain undetected during conventional microscopic analysis, and grain-counting results can be influenced by sampling representativeness and counting procedures. Conversely, XRF quantifies elemental composition but cannot determine which mineral phase hosts a measured element. Therefore, the parallel increase in monazite and zircon abundance and associated elemental concentrations should be interpreted as convergent evidence of enrichment rather than proof of direct mineral–element association. This distinction is particularly important for monazite, xenotime, and zircon because their REE-hosting characteristics differ and require mineral-specific analytical confirmation (Abegunde et al., 2016; Balassone et al., 2024; Möller & Williams-Jones, 2018; Setiawan, 2018).

The strongest enrichment observed in processing residues has important implications for the management of materials conventionally treated as mining waste. Monazite and zircon together accounted for 10.40% of the identified mineral assemblage in processing residues, compared with only 1.43% in tailings, while Y approached 0.951% and substantial concentrations of Nb and Th were also recorded. These findings suggest that successive beneficiation stages produced a residual stream enriched in accessory minerals that were not recovered with the principal tin product. Similar observations have been reported from Bangka, where post-processing tailings contained monazite, xenotime, zircon, ilmenite, and other critical-mineral phases, and from Singkep, where processing of tin wastes substantially increased REE concentrations in mineral concentrates. The present study extends these observations by tracing the mineralogical and geochemical changes from mining-front material through tailings to processing residues within the same processing sequence, thereby providing a process-oriented perspective on secondary mineral enrichment (Adu et al., 2026; Balaram, 2024; Edahbi et al., 2018; Pereira et al., 2021).

Despite these enrichment patterns, the results should be interpreted as evidence of preliminary secondary-resource potential rather than confirmation of an economically recoverable REE resource. The present GCA–XRF approach does not quantify individual lanthanides, establish the mineral hosts of Y, Nb, or Th, determine mineral liberation characteristics, or evaluate metallurgical recovery. The relatively high Th concentration in processing residues also indicates that any future recovery strategy would need to consider the mineralogical distribution and management implications of associated radioactive elements. Further characterization using mineral-specific techniques such as SEM–EDS and XRD, combined with sensitive elemental analysis such as ICP–MS, would be necessary to confirm mineral hosts and quantify individual REE before recovery potential can be assessed reliably. Broader spatial sampling, mineral-liberation analysis, beneficiation testing, and resource and economic assessments are also required to determine whether the observed enrichment can translate into technically and economically viable recovery. Accordingly, the principal contribution of this study lies in establishing a site-specific mineralogical–geochemical baseline and demonstrating the value of integrated characterization for identifying potentially enriched tin-processing residues (Habibi et al., 2026; Khan et al., 2022; Martins et al., 2023; Roy & Venkatesh, 2009).

Conclusions

The integrated mineralogical and geochemical characterization demonstrated that tin-processing materials from the Front Penambangan Desa Bukit Layang, Kecamatan Bakam, Kabupaten Bangka contained accessory minerals associated with Rare Earth Elements (REE). Grain Counting Analysis (GCA) identified progressive enrichment of monazite and zircon from the mining-front material through mine tailings to processing residues. The processing residues provided the strongest mineralogical indication of REE-associated enrichment, while the corresponding X-Ray Fluorescence (XRF) results showed the highest concentrations of yttrium, zirconium, niobium, and thorium in the same material. The consistency between the mineralogical and elemental trends indicates that integrating GCA and XRF provides a stronger basis for interpreting REE-associated mineral occurrence than using either approach independently. The findings are important because they establish a site-specific baseline showing that tin-processing residues may represent a potential secondary source of REE-bearing accessory minerals rather than being viewed solely as residual material. However, the results support a potential assessment, not a definitive claim of economically recoverable REE resources, because individual REE concentrations, mineral liberation, recovery performance, resource quantity, and economic feasibility were not determined. Future work should therefore apply mineral-specific and more sensitive analytical techniques, expand sampling coverage, and evaluate recovery and economic feasibility before any conclusion regarding commercial REE utilization is made. The study thus advances understanding of tin-processing residues in Bangka by linking mineralogical enrichment with geochemical signatures and provides a scientific basis for subsequent investigation of their secondary-resource potential.

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