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Sustainable Gold Recovery from Mine Tailings through Reagent Optimisation and Bottle-Roll Cyanidation: Implications for Small-Scale Mining

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Abstract: Mine tailings can still contain amounts of gold, due to liberation and recovery inefficiencies during primary processing and secondary mineralisation, thus representing the possibility of secondary resource potential and treatment of tailings as an additional source of gold. This paper presents the optimisation of reagent dosage in reprocessing mine tailings for gold recovery from the Klein Letaba mine, using bottle-roll cyanidation, followed by geochemical, statistical, and spatial characterisation. 39 representative samples were collected at approximately 50-m intervals and analysed following fusion-digestion coupled with ICP-OES determination of concentration, with values ranging from 0.20 to 5.30 g/t. Statistical data from R/RStudio show wide grade variation: a mean of 1.157 g/t, a median of 0.800 g/t, and a standard deviation of 0.500 g/t. dev. of 1.079 g/t. Dev and coefficient of variance of 93.25%, and the data is positively skewed (2.155). Ordinary Kriging demonstrates spatial grade variation and concentrated grade pockets, particularly at S08, S32, S35, and S37, enabling targeted investigations & treatment. During 24-h bottle roll cyanidation in alkaline pH, pH ranged from 9.35-10.14, then stabilised at 9.93, Lime: 4.528kg/t and NaCN: 3.074 kg/t were respectively consumed, mobilisation of gold was at 81.5% and transferred into the solution-carbon system 0.484g/t, resulting in a total recovery of 41.3 %. This study provides information and guidelines for the optimum dosage for tailings reprocessing, while further optimisation with respect to leaching, loading and recovery is required

Keywords: Bottle-roll cyanidation; gold recovery; mine tailings; reagent dosage optimisation; small-scale mining; sustainability.

1. Introduction

Mine tailings are basically industrial waste containing sometimes a considerable amount of residual gold due to the inaccuracy or incomplete recoveries during the first processing of mineral ores. The demand for gold has been growing due to technological and socio-economic progress. But high-quality gold deposits are becoming scarce, so the gold market relies on refractory gold ores (Wang et al., 2025). Due to the common constraints of economic and environmental feasibility, the recovery of gold from mine tailings has also attracted broad research interest in mineral processing. The solid wastes produced by several artisanal and small-scale gold mining (ASGM) operations, which recover gold by amalgamation (Teillaud et al., 2025), are likely to be richer in metals compared to industrial process residues, owing to the fact that in an artisanal operation, processing is poorly controlled and metal recovery rates are often low (Youpoungam et al., 2024; Abdallah Mohamed et al., 2025). Mine tailing streams resulting from the leaking and sludging of mining and processing activities are increasingly being generated to satisfy growing metal demands and exploit lower-grade resources through technological advancements (Bueno-Gomez et al., 2025; Vitti and Arnold, 2022; Fereydouni et al., 2025). Hence, as the high-grade mines are getting exhausted, industrial requirements for the basic metals are soaring, prices of base metals are rocketing, and we must consider the environmental protection aspects; it may serve as a secondary source of the metal in which both interests of the stakeholders and the investors may be reconciled (Li et al., 2024; Nakhaei et al., 2025). On top of this, safe reprocessing of mine tailings in order to increase metal recovery and reduce their environmental burden (for example, in Maimekov et al.'s (2025) work, Ca and CaO were used for adsorbing acidic gas and reducing the damage caused to the environment, 2025), benefits sponsors in the investment and research effort for extracting gold from tailings. The degree of gold extraction in the leaching process for tailings treatment largely depends on the selection of reagents and their dosages. According to Sithole and Mashifana (2019), the higher the Sodium Hydroxide (NaOH) concentration, the greater the available NaOH content at a given water content, thereby promoting better activation of gold mine tailings in an alkaline medium. This clearly explains the importance of neutralising the effluent not only to avoid ecological contamination but also to facilitate gold liberation from the host rock. Usually, reagent consumption contributes substantially to the costs of operating gold mining projects. A sustainable future post-closure is achievable, and mining has already proven its major role in diversifying a country's economy (Zvarivadza, 2018).

The optimal reagent dose might be influenced by the risk of underestimation (low efficiency of gold recovery) and the risk of overestimation of precious reagent dosage. It is evident that varying reagent dosages in metallurgical operations have economic and ecological benefits for the recovery grade and process efficiency. A high grade of gold liberated in a very difficult matrix requires a dosage precisely at the mining operation, during the cyanide process of gold recovery. So, there is a strong interest in a better optimisation method for gold process development to optimise reagent dosage. As a laboratory bench scale test for leach process

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investigation, bottle roll testing has become popularly used to evaluate leaching kinetics, even though with the presence of problems from minerals such as hydronium jarosite and sulphides that preclude gold extraction by the conventional cyanidation leach method (Mahamba et al., 2025; Brittan and Plenge, 2015). This type of test mimics the leaching process on a very small scale, providing rapid, repeatable results that can be used to inform scale-up work. The test can be performed to systematically determine reagent consumption and leach kinetics, providing useful information on the feasibility of gold recovery from an inhomogeneous tailings heap, or, at least, representative information on the variability of the resource when used together with a proper sampling strategy (for example, systematic grid sampling). It is therefore the experimental technique selected to initiate optimized reagent packages.

Although many gold-recovery methodologies have been proposed and extensively studied, the current literature notes the deficiency in considering tailing heterogeneity and optimising reagent dosages. As explained by Barbouchi et al. (2025), gold is difficult to recover from refractory ores because the gold particles are entrapped in the sulphide mineral, which may be pyrite (FeS_2) or arsenopyrite (FeAsS). Previously, pyrite (FeS_2) was considered waste material; however, it has recently been shown to contain valuable metals, such as gold (Au) (Chibesa et al., 2025). Many methods utilised were either insufficient or unsuitable sampling techniques (which did not account for spatial variability in gold) or did not use statistics, instead relying on qualitative statements to draw definitive conclusions from the data. The amount of research that integrates detailed sample designs, bottle-roll tests, and computer-based data analysis methods thus appears to be limited. This work addresses this research gap by systematically utilising a grid-sampling technique to evaluate variability in tailings, a bottle-roll controlled test to investigate reagents, and a statistical analysis to optimise the dosage of the selected reagent.

2. Materials and Methods

This study used a mixed approach to achieve the objective. Methods like this are discussed extensively in the sections that follow.

2.1. Mine tailings sampling and characterisation

Representative tailings samples collected during two different sampling episodes, with 17 samples collected during the first, and 22 samples collected during the second, were carried out across the Klein Letaba mining-tailings area (Figure 1). 50m sampling intervals were used, and 39 samples were taken across the study area to gather representative tailings samples. Using an auger, shovel, and pick, approximately 0.5m of material from the upper layer of the loose and brittle tailings was removed from the top of each sample to obtain a representative sample. 1.3 kg of material collected from each point was carefully placed in contamination-free plastic bags, labelled and properly sealed before being sent to the laboratory for testing. For geochemical, mineralogical, and metallurgical studies, consisting of the determination of gold content and a 24h bottle-roll test on the representative samples. All samples were sent to the laboratory for testing. Fig.1 presents a locality map of the mine tailings at Klein Letaba, while Fig.2 shows a batch of samples collected using an auger during mine tailings mapping.

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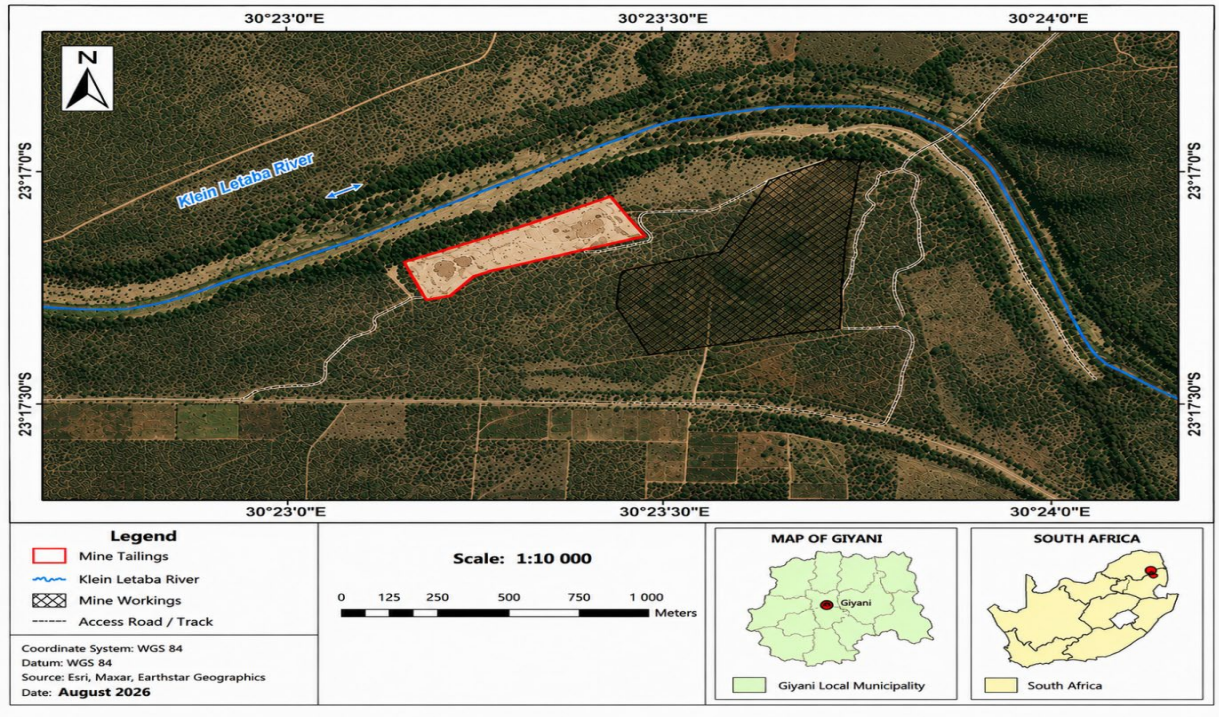

Fig.1: Locality map of the mine tailings at Klein Letaba



Fig. 2: Sample collected using an auger

2.2. Sample preparation and analytical procedures

The collected mine-tailings samples were air-dried, mechanically disaggregated, homogenised, and finely pulverised to produce representative aliquots for gold measurement and bottle-roll testing. To quantify and recover trace metals present in a silicate-rich matrix with efficient matrix decomposition, the mine tailings were

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analysed following a high-temperature fusion digestion method. Known quantity aliquots of pulverised samples were blended with a fluxing material such as sodium peroxide and heated to high temperature in a fusion furnace to create a homogeneous melt, thereby ensuring complete sample dissolution, especially in the case of some mineral-hosted gold species present in the tailings' matrix, which may not be amenable to acid digestion. After cooling, the fused bead was dissolved in dilute acid to obtain a clear solution for ICP-OES analysis. Fig.3 shows the sample preparation flowchart.

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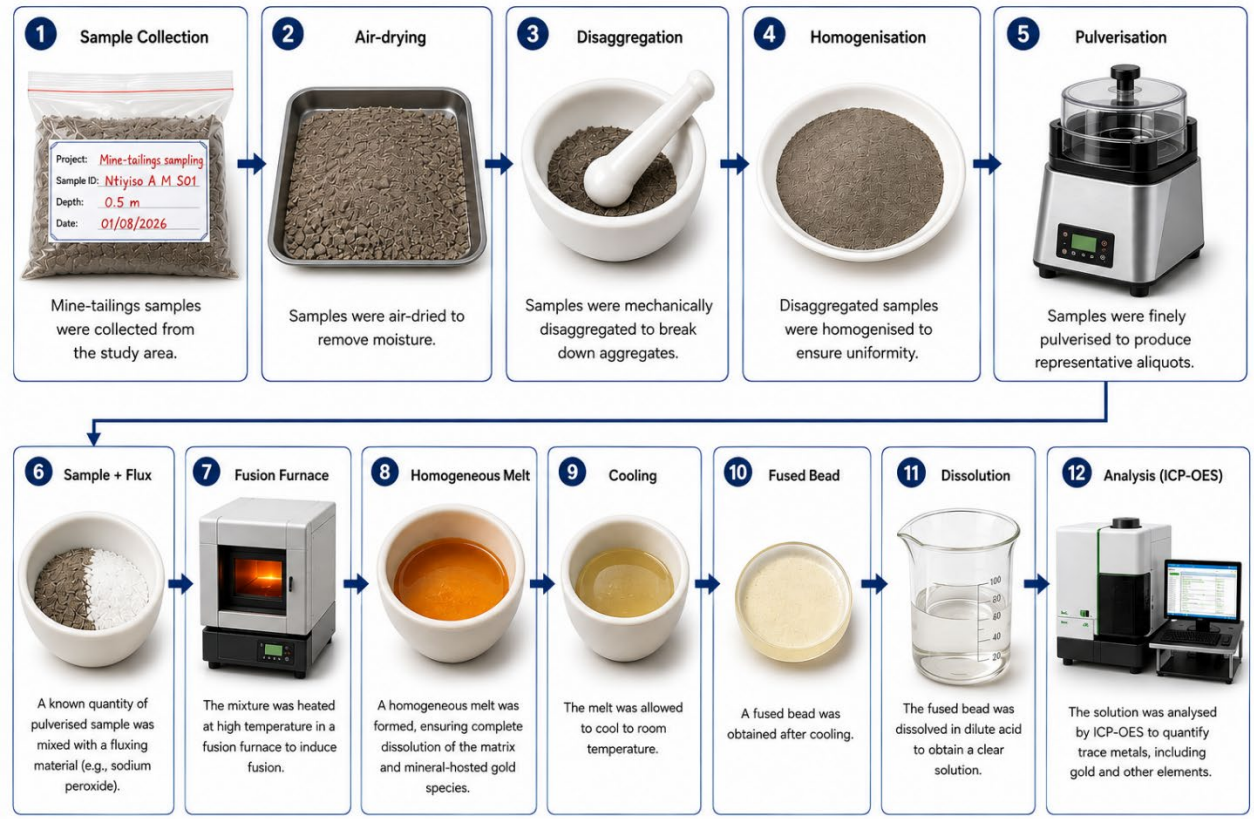

Fig.3: Preparation of mine tailings for ICP-OES analysis

2.3. Laboratory experimental procedure

2.3.1. ICP–OES analysis

The analysis was performed on all resulting solutions for gold concentration using ICP-OES. This is a multielement analytical procedure that relies on monitoring the emission characteristic wavelengths of excited atoms and ions in a plasma created by high-temperature argon gas. Throughout the analysis, solutions of known concentration standards, blank procedural samples, and quality control samples were analysed in parallel to assess the precision and accuracy of the method employed. The intensity of the emitted optical signal was directly proportional to the gold concentration in the mine tailings samples, enabling quantitative determination by comparison with calibration curves. The combined application of fusion digestion and ICP–OES provided a reliable, robust analytical approach for assessing gold concentrations in complex mine tailings, with improved recovery efficiency and reduced matrix interference. The resulting gold concentrations were used as baseline values to evaluate gold recovery in subsequent bottle-roll experiments.

2.3.2. Bottle roll testing for gold extraction

The tailings samples were subjected to bottle-roll cyanidation tests for 24 hours to determine the gold recovery obtainable in the laboratory under controlled conditions at different reagent (NaCN) dosages. These samples were placed into sealed bottles and agitated with sodium cyanide (NaCN) leaching solutions prepared at different reagent concentrations and liquid-to-solid ratios. Activated carbon was used in the solutions to adsorb any gold dissolved from the tailings, and the bottles were rotated to ensure constant contact between the tailings, the cyanide solution, and the carbon. Fig. 4 illustrates the gold leaching experimental procedure.

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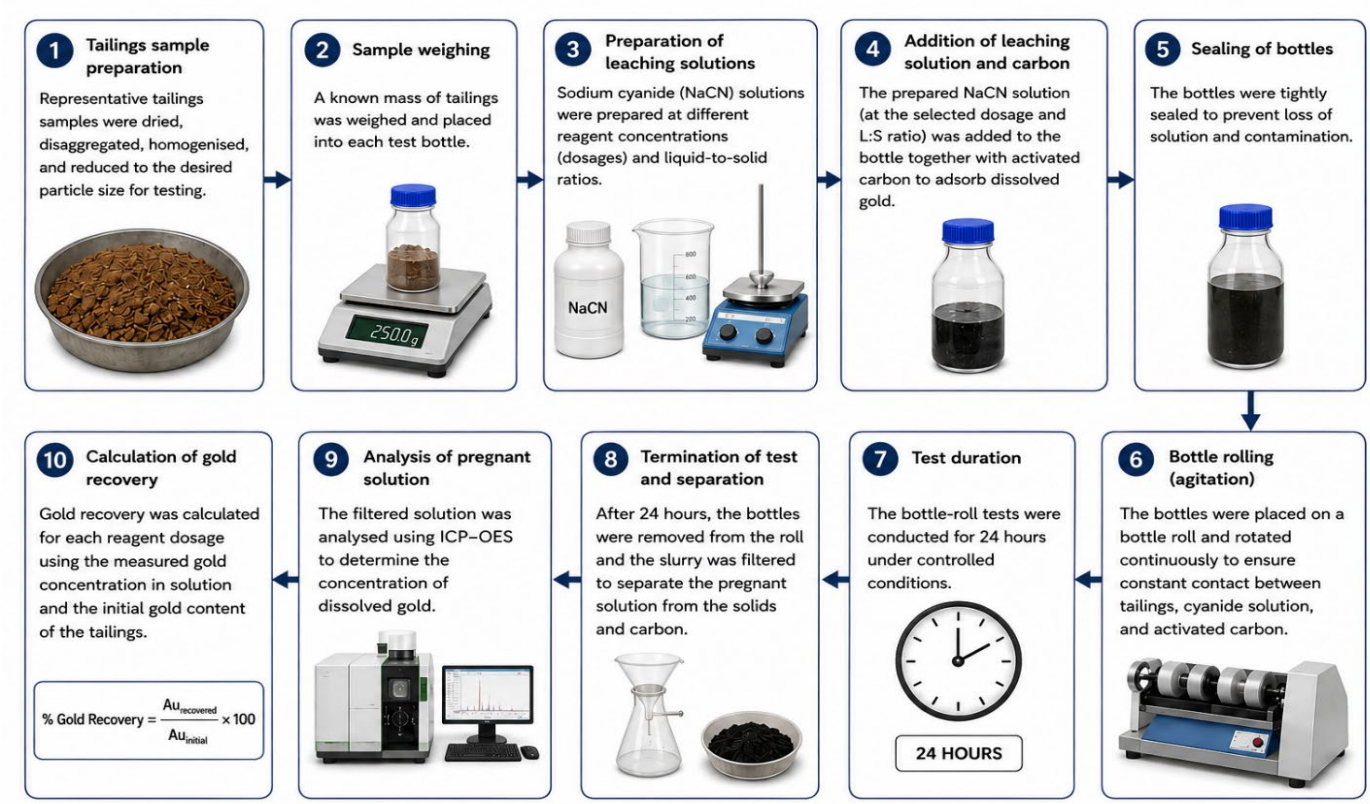

Fig. 4: Illustration of the gold leaching experimental procedure

2.3.3. Reagent dosage optimisation

The optimum reagent for the treatment was determined through a series of gold recovery experiments to determine the optimum concentration for recovery. In each experiment, all operating parameters were held constant as much as possible, whilst varying reagent concentrations to assess the effect of dosage on gold recovery. This experiment aimed to provide information on the relationship between the reagent dosage required for gold recovery and to identify an optimum that achieves satisfactory gold recovery at minimum reagent cost. The recovery achieved at each reagent dosage rate was compared with the tailings reaction to demonstrate the point at which further increases in reagent dose produced no significant increase in gold recovered, thereby assisting in determining the operating reagent dosage.

2.3.2. Gold recovery and data analysis

Gold recovery was determined by comparing the amount of gold transferred into the leach solution to the original amount of gold that existed in the corresponding tailings sample. Results obtained from these experiments were systematically arranged by reagent dosage and other variables under study to enable the treatments to be readily compared. The data obtained then underwent descriptive and comparative statistical analyses to determine variations in gold recovery and the conditions that produce optimal treatment response and extraction. Variability within replicates was also assessed during repeated experiments to determine whether the results were consistent and reliable. The analytical results were eventually summarised in tabular form and shown graphically to emphasise the correlation between reagent dosage and gold recovery.

2.3.3. Geospatial Visualisation and 3-D infographic development

Geospatial visualisation was conducted to understand how gold concentration varies across the sampled mine tailings. A geostatistical tool, such as Ordinary kriging, was used on gold concentration measurements to generate an interpolated spatial distribution model, while R/RStudio was employed for statistical analysis, enabling visualisation of regions of generally lower and higher gold concentrations across the site. The interpolated surface was incorporated into three-dimensional visualisation workflows in Autodesk 3ds Max 2025 (Version 27.0) and Blender (Version 4.2 LTS) for infographic design and high-resolution visualisation of the tailings' physical setting and gold distribution. The three-dimensional model was integrated with the selected experimental data to visualise the relationships among the properties of the tailings, the occurrence of gold within the tailings, the concentration of the reagent used, and the success of the bottle-roll extraction. The

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resulting infographic presents the experimental workflow and key results in a cohesive, visual narrative, preserving the natural relationships among parameters in the raw data while making the implications accessible. By integrating gold distribution with reagent addition and gold recovery, this form of visualisation provided better insights into the experiment, thereby contributing to broader implications for environmental sustainability in small-scale gold mining.

3. Results

3.1. Laboratory Results

3.1.1. Mineralogical characteristics of the mine tailings samples

The study results show that the mineralogy of these mine tailings varies across the region. Quartz, feldspar, and mica are abundant in these rock types with traces of sulphide minerals within the veins and lode structure. Within the alteration assemblage, sericite and chlorite are indicative of low-to medium-grade alteration due to the hydrothermal processes that have occurred. Texture-wise, the sample has been found to be of a disseminated fabric, indicating the dispersal throughout the matrix, whereas quartz-sulphide veinlets show localised fluid-assisted mineralisation.

3.1.2. Initial Gold concentrations results for the round 1 batch of samples

The data resulting from the ICP-OES analysis are spatially controlled and have been used to assess the continuity of the gold grades throughout the study area. The 17 data points have had their x- and y-coordinates (latitude and longitude) recorded, with elevations ranging from 570 to 720 m. This allows the analysis results to be incorporated into the three-dimensional geological and resource model. The gold grades range from 0.44 to 3.48 g/t. This indicates considerable spatial variation in mineralisation. The highest sample grade is 3.48 g/t at the S08 sampling location (elevation 650 m), followed by S09 (2.58 g/t at 650 m) and S16 (2.70 g/t at 580 m). Middle-level grades (S06 - 1.63 g/t, S10 - 1.00 g/t are observed, and below this, most samples are recorded at grades under 1 g/t. It appears that grades are enriched at lower to mid elevations, whereas most of the higher-elevation sampling sites contain grades of less than 1 g/t (S02 - 0.44g/t, S05 - 0.44g/t, S11 - 0.51 g/t). At face value, this suggests a discontinuous and complex mineralised zone in which both geographical location and grade are important factors, along with geological control, sampling density, and the degree of continuity of gold mineralisation, that constrain the gold mineral resource within domains. The corresponding resource estimation results for the round 1 batch of samples are presented in Table 1, which provides gold grades and geological coordinates (X, Y, and Z) for the estimated blocks. The table also shows the allocation of gold between the low- and high-grade domains, as well as the geological and estimation parameters used in the resource model.

Table 1: Gold grades of batch 1 samples determined using inductively coupled plasma optical emission spectrometry

Point	Latitude (S)	Longitude (E)	Elevation (m)	Grade (Au g/t)
S01	23°17′10.00″S	30°23′35.24″E	700	0.87
S02	23°17′08.65″S	30°23′36.80″E	720	0.44
S03	23°17′07.65″S	30°23′38.76″E	710	0.55
S04	23°17′08.65″S	30°23′40.51″E	720	0.83
S05	23°17′10.67″S	30°23′41.74″E	720	0.44
S06	23°17′12.66″S	30°23′35.60″E	700	1.63
S07	23°17′12.01″S	30°23′36.77″E	690	0.72
S08	23°17′11.68″S	30°23′38.10″E	650	3.48
S09	23°17′12.35″S	30°23′40.00″E	650	2.58
S10	23°17′15.37″S	30°23′33.54″E	690	1.00

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S11	23°17′15.03″S	30°23′36.29″E	710	0.51
S12	23°17′14.70″S	30°23′38.38″E	680	0.99
S13	23°17′15.37″S	30°23′41.10″E	650	0.52
S14	23°17′16.04″S	30°23′41.74″E	650	0.79
S15	23°17′18.73″S	30°23′35.34″E	630	0.60
S16	23°17′18.05″S	30°23′36.80″E	580	2.70batch 2
S17	23°17′18.39″S	30°23′38.10″E	570	0.92

3.1.3. Initial Gold Concentrations results for the round 2 batch of samples

The ICP-OES analytical results from round 2 show a range of gold concentrations across samples S18 to S39, indicating lateral variations in gold grade across the sampling locations. The provided dataset of recorded gold grades ranged from 0.20 g/t to 5.30 g/t, indicating substantial lateral variations in gold grades at the investigation locations. There were three locations with gold grades >2.00 g/t-at S35 (with 5.30 g/t at 5.30 g/t at 590 m elevation), at S32 (3.41g/t at 640m), and at S37 (2.39 g/t at 680m), which appears to indicate three distinct anomalies within the sampling locations. Samples at S22 (1.95g/t), S36 (1.79g/t), S18 (1.28g/t), and S20 (1.11 g/t) recorded intermediate Au grades, with almost all the remaining locations showing <1.00 g/t. Using geographic coordinates (latitude, longitude, and elevation) to report analytical data is suitable for incorporating geochemical data into a three-dimensional geological and resource model. The fact that high gold grades were particularly located at relatively low-elevation sites such as S35 and S32 illustrates that there is variation in geology and grades in both vertical and lateral directions. The low gold grades observed at S39 (0.20 g/t) and S24 (0.24g/t) are used for constraining the boundaries of mineralised domains. It is considered that an element of gold grade variation is present at the measured locations, and the data can contribute to building a 3-dimensional geological/resource model of the area. In Table 1, all geological and resource-estimation parameters of the round 2 batch of samples used to prepare a geology-based mineral resource model are listed.

Table 2: Gold grades of batch 2 samples determined using inductively coupled plasma optical emission spectrometry.

Point	Latitude (S)	Longitude (E)	Elevation (m)	Au Grade (g/t)
S18	23°17′08.20″S	30°23′33.20″E	710	1.28
S19	23°17′15.00″S	30°23′35.00″E	640	0.95
S20	23°17′11.50″S	30°23′40.00″E	680	1.11
S21	23°17′06.80″S	30°23′35.20″E	720	0.40
S22	23°17′08.50″S	30°23′37.80″E	700	1.95
S23	23°17′10.80″S	30°23′36.80″E	690	0.52
S24	23°17′06.20″S	30°23′40.20″E	720	0.24
S25	23°17′11.80″S	30°23′38.20″E	670	0.95
S26	23°17′13.50″S	30°23′45.00″E	630	0.36
S27	23°17′06.00″S	30°23′43.00″E	720	0.32
S28	23°17′08.00″S	30°23′42.00″E	700	0.36

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S29	23°17′10.00″S	30°23′43.50″E	680	0.80
S30	23°17′14.00″S	30°23′40.00″E	620	0.64
S31	23°17′14.50″S	30°23′45.00″E	610	0.64
S32	23°17′11.00″S	30°23′41.00″E	640	3.41
S33	23°17′06.50″S	30°23′47.00″E	720	0.84
S34	23°17′08.50″S	30°23′45.00″E	700	0.64
S35	23°17′17.00″S	30°23′42.00″E	590	5.30
S36	23°17′17.00″S	30°23′39.00″E	580	1.79
S37	23°17′10.00″S	30°23′47.00″E	680	2.39
S38	23°17′07.00″S	30°23′50.00″E	720	0.48
S39	23°17′19.00″S	30°23′41.00″E	560	0.20

3.1.4. Statistical analysis of gold concentrations using R/RStudio

The overall R/RStudio statistical characteristics results indicate a high degree of heterogeneity in gold concentrations present in the explored Klein Letaba mine-tailings area. A mean gold concentration of 1.157 g/t and a median of 0.800 g/t indicate a positively skewed distribution of the gold assay results, which range from 0.20 to 5.30 g/t (5.10 g/t range). This variable nature is also illustrated in the relatively high standard deviation (1.079 g/t) and coefficient of variation (93.25%). Skewness value of 2.155 clearly points towards the fact that it was a few high-grade samples influencing the overall average significantly- namely S08 (3.48 g/t), S16 (2.70 g/t), S32 (3.41 g/t), S35 (5.30 g/t), and S37 (2.39 g/t). The 50% range, from 0.515 to 1.195 g/t (Interquartile range = 0.680 g/t), indicates that most samples contain low gold concentrations. Such statistical characteristics support the interpretation of highly variable, locally concentrated gold amounts and confirm the need for spatial modelling and targeted sampling to effectively evaluate the feasibility of secondary gold recovery from tailings. Fig. 5, 6 and 7 provide graphical and statistical extensions for the gold distribution.

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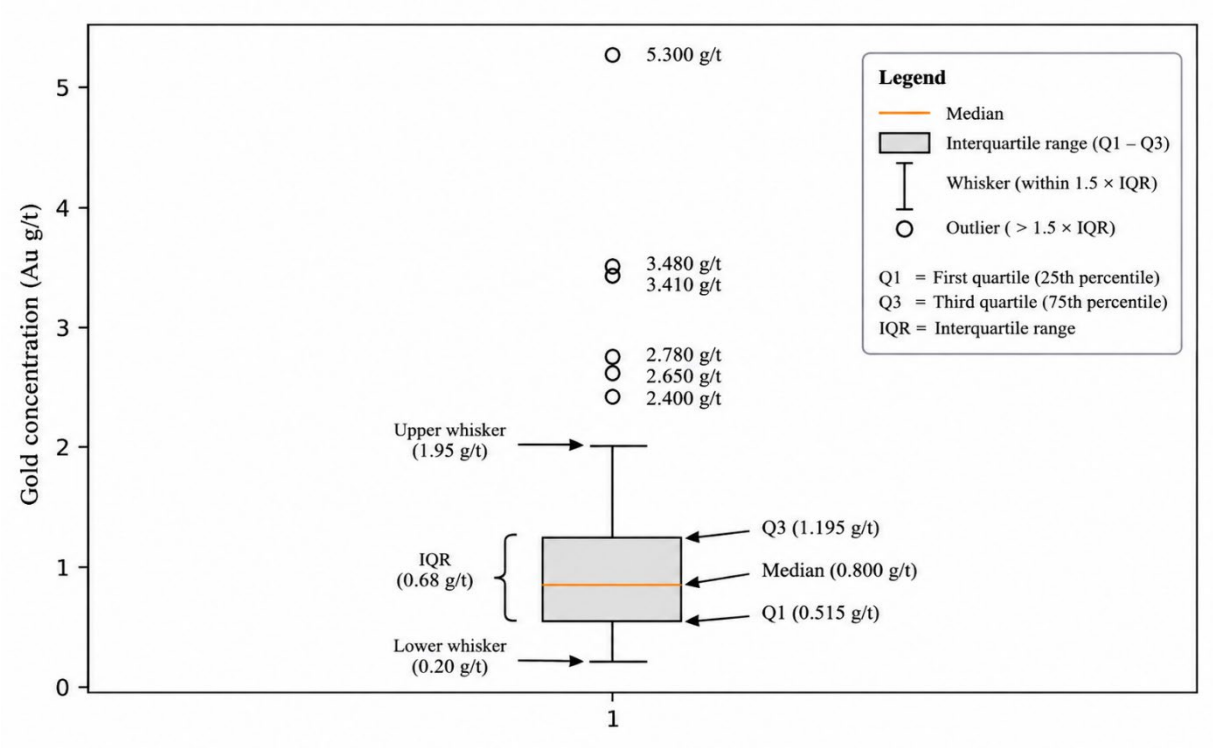

Fig.5: Graphical presentation of the box-and-whisker plot of gold concentration

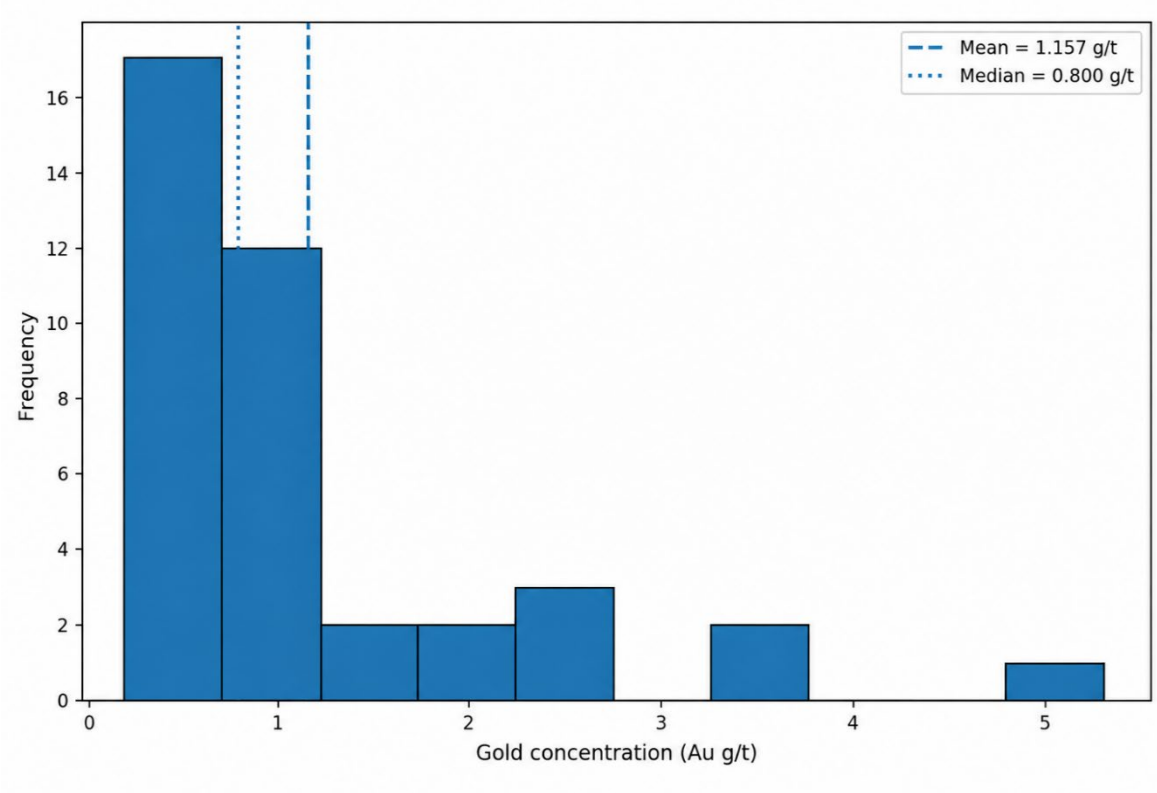

Fig.6: Graphical presentation of the distribution of gold concentration

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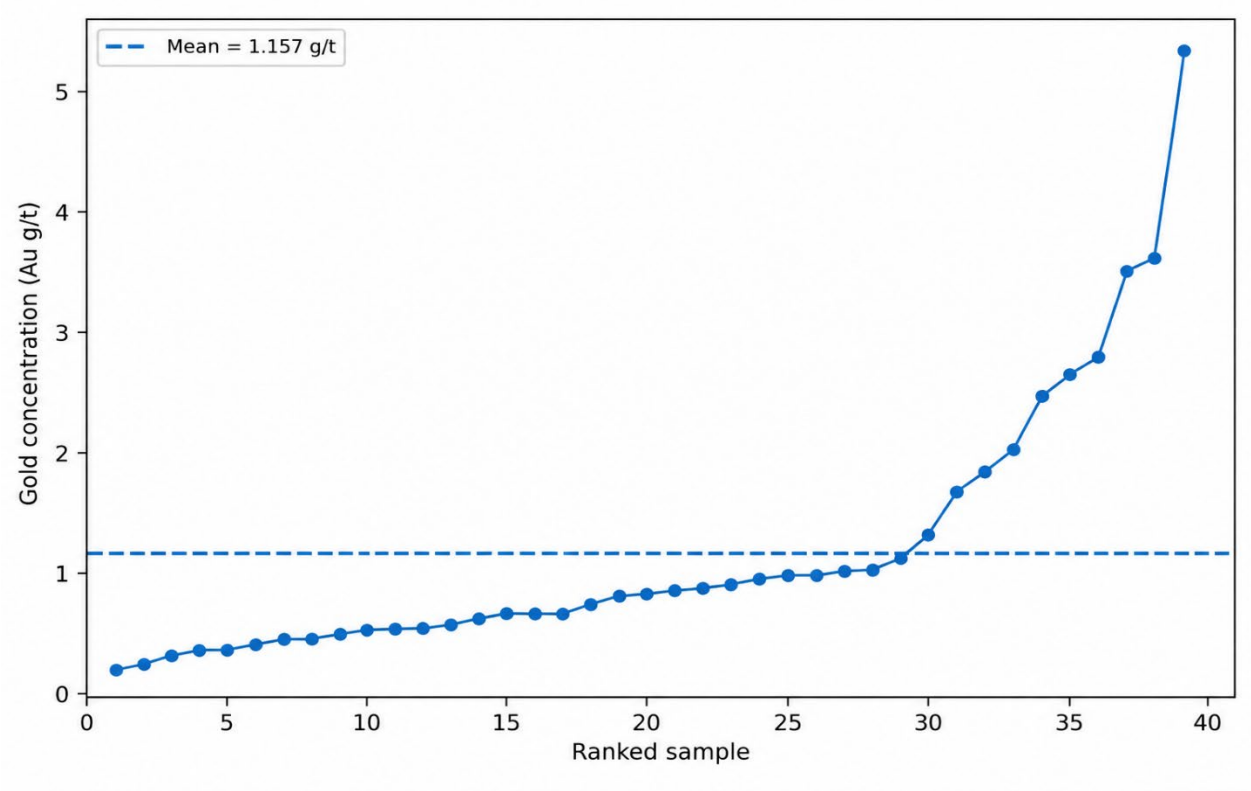

Fig. 7: Graphical presentation of ranked gold concentrations

3.1.5. Geostatistical and spatial analysis of gold concentrations

The geostatistical models under consideration were developed based on the data presented in Tables 1 and 2 in sections 3.1.2 and 3.1.3, respectively. The Ordinary Kriging analysis maps illustrate the spatial distribution and variability of gold (Au) concentrations in the Klein Letaba mine-tailings area, utilising 39 sample points. The Kriging prediction map shows considerable spatial variability, with high Au concentrations only at and around S08, S32, and S35, while concentrations are comparatively lower in several areas in the northern part of the study area and in the southeastern region. The Kriging variance map shows lower estimated variance in areas of greater sampling support, with higher variance values along some of the study area's extremities. The high- and low-grade zone map delineates comparatively enriched areas where grades > 2.0 g/t Au occur, along with low-grade zones where Au concentrations < 0.5 g/t occur, with clear contrasts relative to the gold distribution. The 3D spatial model further illustrates the distribution and location of concentration within the mine tailings' three-dimensional space and strongly emphasises the enrichment around S08, S32 and S35. Combined, the maps depict substantial spatial variability in Au concentrations and areas that warrant further investigation to identify locations of enrichment for the possible recovery of gold through the repurposing of tailings. Fig. 8 presents the three-dimensional spatial distribution of gold concentrations at the Klein Letaba Mine Tailings.

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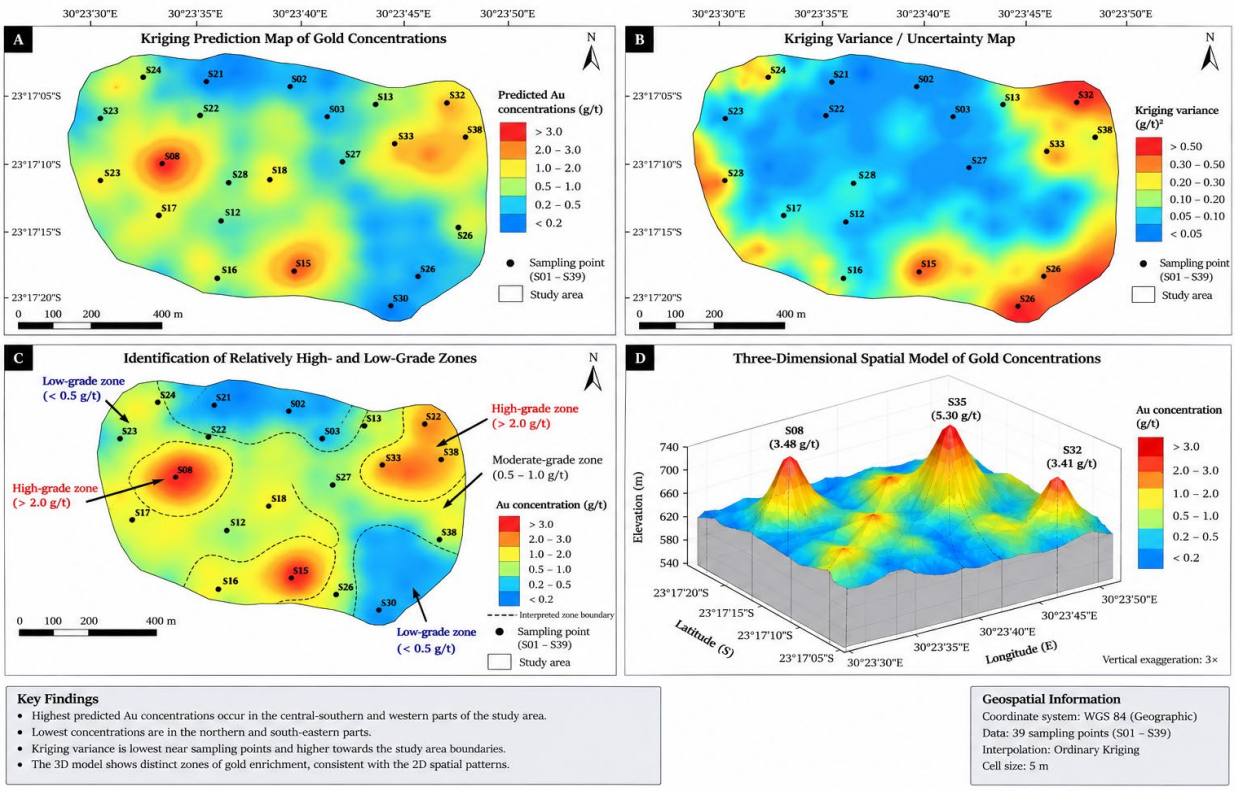

Fig.8: Three-dimensional spatial distribution of gold concentrations at Klein Letaba mine tailings

3.1.4. Bottle-roll gold recovery

The laboratory bottle-roll leach of the sample has been conducted to optimise the environment for gold dissolution. The dissolution efficiencies shown for the bottle roll test indicate a gold mobilisation from the ore to solution of 81.5%, as given in the above section (the proportion of the gold dissolved into solution with respect to the initial gold in the ore). The finer grind will increase the reactive surface area of gold, thereby increasing its reaction with the leaching reagents. Leaching occurred in an alkaline environment at a pH which started from 9.35, reached 10.14 after 12 hours, and then stabilised at 9.93 at the completion of the tests. At this pH, the additional 4.6 kg/t CaO should provide sufficient cyanide stability to minimise volatilisation losses and facilitate gold-cyanide complexation. The total weight of gold transferred to either solution carbon systems (0.000484 kg/t) and the dissolution efficiency (41.3%) provide further support for the controlled partial mobilisation/transfer to soluble/easily adsorbable forms.

3.3.5. Effect of reagent dosage on gold recovery

The test conditions thus also allowed a systematic evaluation of reagent behaviour, focusing chiefly on lime and sodium cyanide, both of which are critical to the cyanidation process. Reagent consumption suggested 4.528 kg/t of lime and 3.074 kg/t of NaCN, values that align well with industry norms for efficient operation in low-to-moderate sulphide ores. The lime dosage maintained an alkaline environment throughout the leaching cycle, as evidenced by the recorded pH values. In addition, the titration results revealed that the remaining lime value was 0.072 kg/t and the residual NaCN was 0.126 kg/t. This suggests that not only was there a small quantity of reagent waste, but also a significant surplus to ensure process control. The precise regulation of reagent dosing is critical to balancing economic and metallurgical considerations. The dissolution values for the solution and carbon phases (e.g., 0.002 in solution, 49 in carbon) indicate that NaCN effectively mobilised gold from the ore matrix into both free solution and adsorbed phases. These findings suggest that the reagents operated under optimal kinetic and thermodynamic conditions, enabling both solubilisation and subsequent carbon capture of gold. Fig. 9 shows cyanidation leaching reagent control.

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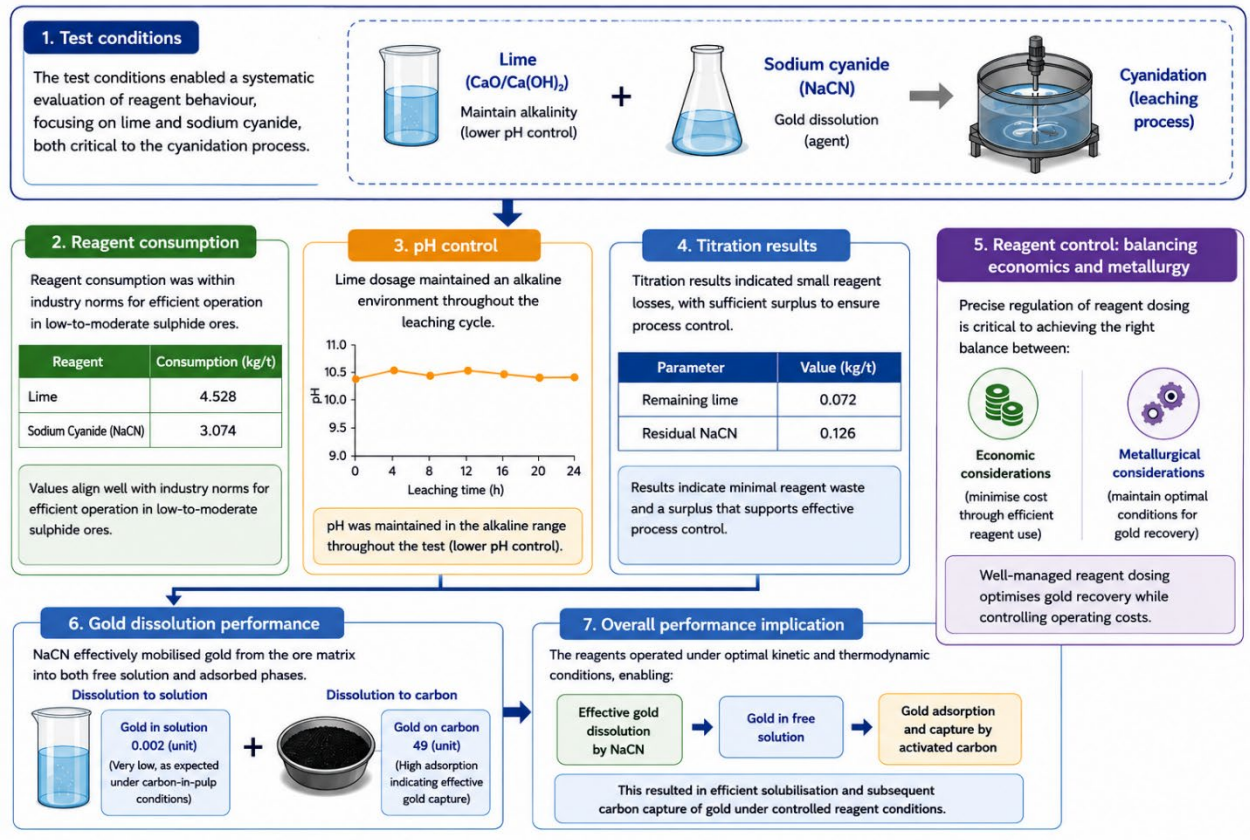

Fig. 9: Cyanidation leaching reagent control

3.3.6. Performance of reagents and overall system effectiveness

The results revealed a performance of reagent optimisation in overall cyanidation, showing good cyanidation efficiency, a stable alkaline solution, high reagent usage, and high gold mobilisation. It showed gold mobilisation value 81.5%, proves that the specific conditions utilised resulted in higher amounts of gold leaching from the tailings material, where 0.484 g/t was found to be transferred to the solution-carbon system indicating that a recovery of 41.3 % could be attained when such leaching is combined with carbon absorption system based on value presented by others, (Lime of 1.59% and Na CN was 4.10% indicates good efficiency utilisation of the reagents during 24-hr test). However, inconsistency between the amount of gold mobilised in the leaching process and that found in the entire system indicated that a proper optimisation of the leaching phase and gold capture needs to be developed in order for high recovery, and also can be used as a good reference in future process development on achieving economical reagent application for sustainable Small Scale Mining (SSM), as in the case for Ka-Mapuva village.

4. Discussion

4.1. Mineralogical controls on gold occurrence, liberation and recovery

The tailing's mineralogy combines all the factors that govern the material's complexity and potential. According to Dominy et al. (2018), to determine the effect of materials on recovery, the type and style of gangue and mineralisation must be considered. The study's outcomes revealed the presence of mineral assemblages, such as quartz, feldspar, and mica-dominated assemblages, with a highly siliceous gangue that is usually impervious to chemical attack during processing, thus limiting gold liberation. Therefore, mineralogy and ore characterisation play important roles in advancing mineral processing (Roostaei et al., 2025). The low proportion of sulphides is worth noting, as sulphides are often associated with refractory gold or may form passive layers that render gold cyanidation inefficient (Gkdemir et al., 2025). The nature of alteration minerals such as sericite and chlorite suggests that the primary mineralogy has undergone hydrothermal alteration, which might lead to the redeployment of gold in veinlets or microfractures. The textures of quartz–sulphide veinlets and scattered phases suggest a patchy distribution of gold, and it is most likely associated with the sulphide phases and fracture networks. Variations in mineralogy explain the difficulty of achieving consistent extraction in small-scale operations, while residual gold in tailings also poses a processing challenge. This finding is consistent with the body of research that integrates geoscientific disciplines with minerals and mining

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engineering to produce optimised, more resilient operations on artisanal mining residues, as highlighted by Dominy and Glass (2025), which suggests that gold sulphide-bound and silicate-hosted material remains partially recovered. According to Zeb et al. (2025), the shifting societal preference towards environmental and social sustainability makes it paramount for large industries such as mining and metallurgy to operate efficiently. Hence, mineralogical characterisation points to structural and chemical difficulties hindering full recovery, while suggesting approaches for recovery techniques.

4.2. Spatial Gold Heterogeneity and Implications for Sustainable Small-Scale Mining

The heterogeneity observed in the primitive distribution of gold values confirms that artisanal mining methods produce highly variable recovery outcomes. The presence of high-value anomalies, such as in samples S35 and S08, indicates that large quantities of gold remain in small pockets, possibly due to inadequate liberation or inefficient extraction processes. This finding is in accordance with the study by Dominy et al. (2021) on the determination of gold particle characteristics, where it was reported that mineral deposits with commercially viable concentrations of gold, that is, coarse gold greater than 15% by weight and greater than 100 µm in size, usually exhibit a high nugget effect. This situation further accentuates the limitations of primitive processing methods, which do not uniformly liberate the ore minerals. From an economic standpoint, these anomalies are worth re-mining with more advanced technology, but from an environmental perspective, they represent zones where metal loadings occur, which can leach into the ecosystem if left unchecked. Therefore, Au mineralisation appeared to be more indirect relative to many shearing and complex structures (Gobashy et al., 2023). The moderate concentration values that predominated in many samples in the study area illustrate the middle case, where small-scale operators might have capitalised by leveraging upgrades to low-cost technologies to treat residues. Lower-value samples do demonstrate, however, that there was sometimes an adequate recovery efficiency, although the association of these samples with higher-value ones reflects irregularities in how these ore bodies were processed. That spatial variability is consistent with artisanal ore blending, whereas standardised treatment is rarely applied. Conceptually, the insoluble patterns of value speak for both the inefficiency and the potential of artisanal mine tailings as secondary gold sources.

4.3. Gold-Grade Variability and Recovery Implications

The statistical profile of gold concentrations provides further insight into the variability in the recovery already identified in the raw data. The strong positive skewness and leptokurtic distribution in nature confirm that the dataset contains an excess of low values and few extremely high values, consistent with both overall inefficiency and locally efficient extraction, as suggested by Chen and Xiao (2025). The results show that the mean being higher than the median confirms the greater influence of certain high-value outliers, such as sample S35, which, on the upside, conspicuously distorts the view of the sample's gold content. However, according to Iacobucci et al. (2025**)**, outliers are described more as a function of scientific agreement, as "an experience (or subset of discoveries) that tends to be contrary to the rest of that set of data. The narrow Interquartile Range (IQR) concentrated at the lower end of the distribution points out that most samples hold only modest gold values, while the extreme outliers represent exceptional cases. Thus, one main implication of adopting the quantile approach is avoiding the unnecessary influence of outliers on the traditional moment-based measures: variance, skewness, and kurtosis (Chen and Xiao, 2025). For this reason, a process evaluation lens, such as statistical asymmetry, suggests systemic inefficiencies in mineral liberation that allowed discrete zones of high retention. The high variance and broad ranges compound the unpredictability of the consequences of artisanal extraction, thereby hindering resource estimation and environmental risk assessment. The statistical pattern indeed aligns with the small-scale mining-residues study results, which consistently document non-normal distributions of residues due to uneven processing control. Hence, the statistical summary provides heterogeneity and backs the argument for systematic re-treatment options.

4.4. Influence of Particle Size on Gold Dissolution and Recovery

The bottle roll leaching test greatly exemplified the influence of well-optimised operational factors on gold recovery efficiency. The dissolution efficiency of 81.5% attained in fine-particle-size operations reflects the fundamental principle that surface availability is an important factor in wet leaching kinetics. This suggests that the 81.5% in the Head - Waste/Tails can be improved by combining it with tailored leaching in the metallurgical flowsheet, thereby substantially enhancing gold recoveries, as highlighted by Chingwaru et al. (2025). The dominance of particles below 75 µm greatly increased reagent contact, thereby enabling deep penetration of cyanide and its complexing with gold. Therefore, the predominance of the fine particle size distribution in the -75 µm fraction can be attributed to the optimisation, which aligns with the findings of Nwaila et al. (2025), who reported an 85% recovery of the 75 µm fractions from bottle roll testing. In addition, Ardian et al. (2025) emphasised that monodisperse particles are frequently used to study the impact of ore particle size on gold recovery, further supporting the outcomes of this study.

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Adequate control of alkaline conditions, with pH maintained close to 10, was beneficial for stabilising cyanide species against volatilisation and decomposition. Alkali activation of mine tailings is a possible low-cost treatment for producing matrices that can immobilise hazardous elements (Kiventerä et al., 2018; dos Santos et al., 2022) and offers a cutting-edge approach to managing mine tailings, as suggested by Kiventerä et al. (2020). Based on the study's outcomes, lime was used to control pH and limit the formation of hydrogen cyanide, a major safety and environmental concern. While gold transfer occurred in solution and into the carbon phases, an illustration of effective gold mobilisation, cyanide also allowed adsorption for downstream recovery. Dissolution and capture balance would constitute an optimised system equilibrating between thermodynamic and kinetic considerations. Altogether, these results show that controlled leaching environments can be used to boost recovery beyond that achieved in artisanal contexts. Considering the above, the study's finding is strongly supported by Lemos et al. (2021), who highlighted that studying the mineralogy of the tailings helps elucidate mineral associations, mineral liberation, and, consequently, the potential for metal recovery.

4.5. Reagent Optimisation, Gold Recovery and Sustainability Implications

The formation of metal-cyanide complexes (with metals such as Cu, Zn, Fe, Co, and Ni) increases cyanide consumption and can affect gold mobilisation in the gold extraction process, both of which are key parameters that define the efficiency and economics of operation (Li et al., 2025). In this study, lime and sodium cyanide (NaCN) were consumed at 4.528 and 3.074 kg/t, respectively. The values indicate effective control of reagents used during the bottle roll test. This was confirmed by measuring residual lime and NaCN at 0.072 and 0.126 kg/t after the gold leaching process finished, suggesting that most of the added lime and NaCN were consumed to achieve the target dissolution rates; however, residual amounts are required to maintain proper reaction conditions. In cyanidation, the effective use of chemicals is critical; they cannot be added at levels below optimal, as this will reduce extraction and worsen economic and environmental outcomes. Studies have previously demonstrated the importance of chemical addition in increasing gold recovery compared with no chemical treatment, as well as in recovering gold from complex secondary gold resources (Surimbayev et al., 2025; Li et al., 2025). Using a combined CaO and NaCN provided the ideal alkaline medium required for gold dissolution and enabled the adsorptive recovery of gold by activated carbon. From the above results, a reported gold mobilisation of 81.5% was found while overall gold recovery was 41.3%. Even though 81.5% of the gold was mobilised into solution, this percentage does not reflect the recovery. Mobilisation of gold into the solution may not be equal to its recovery in the process due to factors such as an inappropriate process and insufficient recovery steps. This is shown by comparing with gold mobilisation of 81.5% and recovery of 41.3%. This phenomenon is well known and has been demonstrated by studying process parameters to improve gold recovery and minimise gold mobilisation, as reported by Zhang et al. (2022), where gold recovery of 81.8% in the as-prepared calcine increased to 93.6% after mechanical activation, a change linked to the degree of gold liberation. Similarly, Qin et al. (2021) show the potential of hydrometallurgical treatment in gold recovery from refractory gold sulphide ore. Both show how the mineralogy of gold-associated ores needs to be investigated and consider different process parameters (particle size, chemical addition, residence time).

5. Conclusions

This investigation provided a clear basis for considering Klein Letaba mine tailings as a possible secondary gold resource and for assessing the viability of their sustainable reprocessing through the coupled application of geochemical, spatial, and metallurgical characterisation. Analyses of the 39 samples revealed noticeable spatial variability in gold concentrations, ranging from 0.20 to 5.30 g/t Au, with notable enrichment localised in certain zones, indicating uneven gold distribution and opportunities for targeted reprocessing. Data integration of assay value with 3-D modelling aided in defining areas of enriched grade, providing a basis for resource evaluation. Bottle-roll cyanidation demonstrated that, by adequate control of the chemical reagents, significant amounts of gold can be mobilised under alkaline conditions. In the 24-hour test, the pH increased from 9.35 to 10.14 before reaching a steady state of 9.93, with lime and NaCN doses of 4.528 kg/t and 3.074 kg/t, respectively. With 0.072 kg/t of lime and 0.126 kg/t of NaCN in the solution/solid phase, it could be stated that great consumption of the reagent takes place. The mobilisation gold amount reached 81.5%; however, only 0.484 g/t Au was transported to the solution-carbon system. The amount, expressed as a recovery rate, was 41.3% for total gold, indicating that specific conditions were needed to improve gold loading and subsequent recovery on the carbon. The overall conclusion of the study is that applying controlled reagent dosage can strengthen the technical case for reprocessing and aid efficient resource use. This means that for operational-scale implementation, the optimum dosage, particle size, residence time, loading rate, and recovery parameters must be defined and supported by a socio-economic study. Based on this, we demonstrate that, in this work, we improve the optimisation of reagent dosage. And that makes our investigation support the small-scale gold mining industry in transitioning from a rudimentary subsistence livelihood to an industry grounded in sustainability and economic feasibility, strongly impacting poverty alleviation and empowerment, SDG #1.

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Furthermore, our study aligns with SDG #9: Build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation.

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Declaration of competing interest

The author declares no conflict of interest.

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