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Environmental beneficiation of Kalmakyr Copper-Molybdenum ore by Pre-flotation Gold-Silver Gravity Recovery

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Abstract

Improving recovery of valuable metals before tailings generation is an important component of resource-efficient mineral processing. This study evaluates the environmental significance of pre-flotation gravity recovery from Kalmakyr copper-molybdenum ore, Uzbekistan, by comparing a laboratory 30-KS shaking table with an FLSmidth Knelson KC-MD3 centrifugal concentrator. The assessment combines metallurgical performance with screening indicators relevant to environmental management: concentrate mass pull, gold and silver recovery, metal upgrading, and preservation of copper in the downstream flotation feed. Grinding for 20 min produced 70.3% material finer than 0.074 mm. The best tested shaking-table condition, 110 min-1 at 10 mm amplitude, recovered 21.91% Au and 24.60% Ag into 1.20% of the feed mass and preserved 99.55% of Cu in the gravity tailings. The 65 G Knelson condition recovered 24.94% Au and 20.80% Ag into 0.92% of the feed mass while preserving 99.27% of Cu. Gold upgrade ratios were 18.3 for the shaking table and 27.1 for the Knelson concentrator; corresponding silver upgrade ratios were 20.5 and 22.6. Thus, a small pre-flotation concentrate captured approximately one-fifth to one-quarter of the gravity-responsive precious-metal inventory without substantial copper diversion. This result indicates a resource-conservation opportunity and a potential reduction of valuable-metal loading to final tailings. Because electricity, water, reagent consumption, and final flotation-tailings quality were not measured, the study presents an environmental screening rather than a complete life-cycle assessment.

Keywords: Kalmakyr deposit; sustainable mineral processing; resource efficiency; mine tailings; gravity separation; gold recovery; silver recovery; copper flotation.

Introduction

Mineral beneficiation influences energy demand, water use, reagent consumption, resource depletion, and the quantity and composition of residues sent to tailings storage[1-4]. Life-cycle studies show that the environmental profile of metal production is strongly site-specific and depends on ore grade, electricity supply, mineralogy, concentrate quality, and the treatment of mine residues[1-5]. Consequently, recovery of valuable minor metals before they enter the main flotation and tailings streams is relevant not only to metallurgical accounting but also to resource conservation and waste management.

The Kalmakyr (Qalmoqqir) deposit in the Almalyk mining district of Uzbekistan is a major porphyry Cu-Au-Mo system hosted by a Late Carboniferous intrusive complex[6-13]. Copper is the dominant economic component, whereas gold, silver, molybdenum, and other associated metals provide additional value. Loss of these associated metals to tailings represents inefficient use of an extracted resource and leaves potentially recoverable metal in a long-term waste facility. A selective pre-flotation stage should therefore recover a meaningful precious-metal fraction at low mass pull while retaining copper-bearing sulfides for the principal flotation circuit.

Gravity separation uses density, size, shape, and hydrodynamic response and generally requires fewer chemical reagents than flotation[7-9]. Shaking tables apply a conventional gravity field, while Knelson concentrators increase the effective gravitational field and can retain fine dense particles[10-14]. Their environmental relevance depends on whether useful metal recovery is achieved at a small mass pull without simply transferring large quantities of gangue or copper minerals into a separate product.

Studies of gravity-recoverable gold, free-gold characterization, gravity-gold technologies, and recovery from copper flotation circuits further motivate the integration of gravity separation with flotation[15-18]. Recent beneficiation literature has emphasized enhanced-gravity concentration, particle-size effects, and the integration of gravity separation with downstream flotation[7,10,12,16]. For Kalmakyr ore, comparative information on the response of a conventional shaking table and an enhanced-gravity Knelson concentrator under controlled laboratory conditions remains limited. A direct comparison is therefore useful for assessing whether a small gravity concentrate can recover part of the Au–Ag inventory while preserving the copper-bearing stream for downstream flotation.

Accordingly, the objective of this study was to compare the metallurgical and screening-level environmental performance of a 30-KS shaking table and a Knelson KC-MD3 concentrator applied before flotation of Kalmakyr ore. The tasks were to i. characterize grinding relevant to flotation-feed preparation, ii. identify the highest-performing tested condition for each gravity device, iii. compare Au, Ag, and Cu grades and recoveries, iv. quantify mass pull, precious-metal upgrade ratios, and copper preservation, and v. define the environmental benefits that are supported by the experimental data while identifying the additional measurements required for a complete environmental assessment.

Materials and Methods

Study material and sample preparation: Ore samples were collected from several areas of the Kalmakyr deposit in the Almalyk district of Tashkent Region, Uzbekistan. The ore-bearing assemblage is associated with diorite–syenite rocks and granodiorite-porphyry intrusions. The laboratory program was designed to provide representative subsamples for particle-size analysis, grinding, gravity concentration, flotation-related evaluation, and chemical analysis.

Sample preparation comprised staged screening, crushing, repeated mixing, and sample reduction. Screening was carried out at 25 mm, 15 mm, and 0.5 mm; oversize material was crushed and returned to the corresponding screening stage. The reduced −0.5 mm fraction was divided into reserve material, sieve-analysis material, technological-test material, and material for further grinding. The final analytical/flotation branch was ground to approximately 0.074 mm (Figure-1).

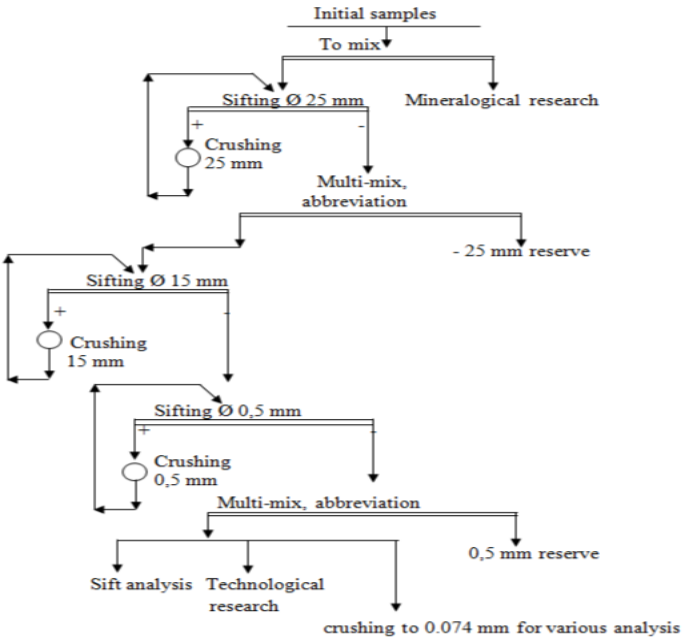


Figure-1: Sample-preparation and splitting workflow used for the Kalmakyr ore samples.

Grinding and flotation-related tests: Grinding was performed in an MSL-30K rod mill and an MSHL-7 laboratory ball mill with a reported volume of 40 L. The solid: liquid: ball ratio was 1:0.75:8. For flotation preparation, 1 kg charges were ground in the MSHL-7 mill and tested in an FML-0.3 (189 FL) laboratory flotation machine. Grind levels corresponding to 57%, 60%, 65%, 70%, and 80% passing 0.074 mm were examined. The archived dataset provides the grinding-time relationship and the key flotation response at the selected grind, but does not contain the complete per-level flotation table for all five grind fractions.

Table-1: Dependence of the −0.074 mm fraction on grinding time.

Grinding time, min	0	10	20	30
Fraction −0.074 mm, %	8.94	45.7	70.3	85.1

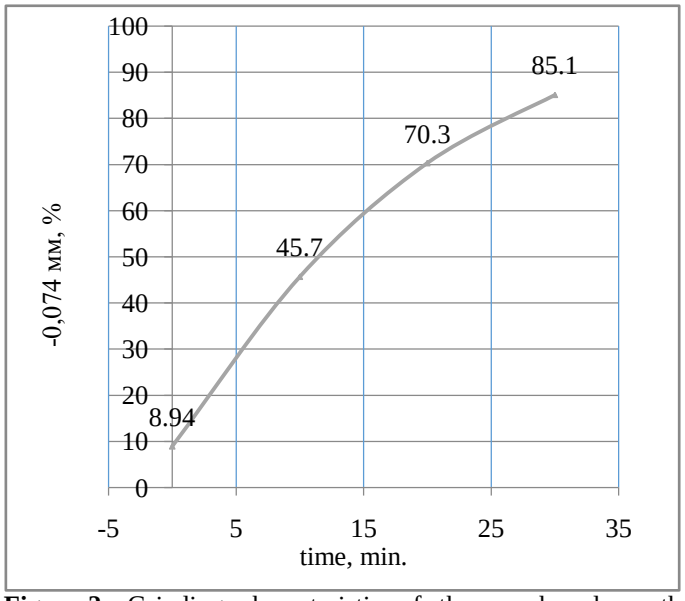


Figure-2: Grinding characteristic of the ore based on the measured -0.074 mm size fraction.

Shaking-table gravity separation: Gravity separation was evaluated on a laboratory 30-KS shaking table using a fine feed fraction designated as -0.1 + 0 mm. The investigated table-frequency range was 100-120 min^{-1} and the amplitude range was 8–12 mm. The transverse deck slope was 7-10°, the initial ore mass was 4 kg, and wash-water flow was 4.5-5.0 L/min. Three paired operating conditions were compared: 100 min^{-1}/8 mm, 110 min^{-1}/10 mm, and 120 min^{-1}/12 mm.

Each test produced a gravity concentrate, middlings, and gravity tailings. The selection of shaking-table variables is consistent with the established dependence of gravity separation on deck motion, particle size, density, and hydrodynamic transport[7-9] (Figure-3).

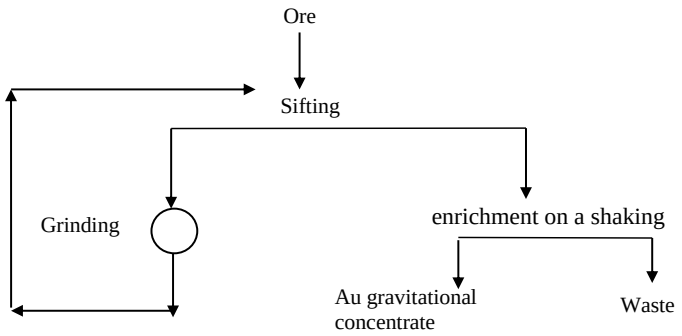


Figure-3: Experimental flow sheet for the 30-KS shaking-table tests.

Knelson centrifugal concentration: Enhanced-gravity tests were performed with an FLSmidth Knelson KC-MD3 centrifugal concentrator. A 1 kg sample with a particle-size range of -0.1 + 0 mm was treated at centrifugal accelerations of 55 G, 65 G, and 75 G. Fluidization-water flow was maintained within 3.5-4.0 L/min, and the reported cycle duration was 10-15 min. Each test produced a gravity concentrate and gravity tailings. In the Knelson separator, dense particles migrate toward the retention zones under centrifugal acceleration while fluidization water limits excessive bed compaction[10,14,17] (Figure-4).

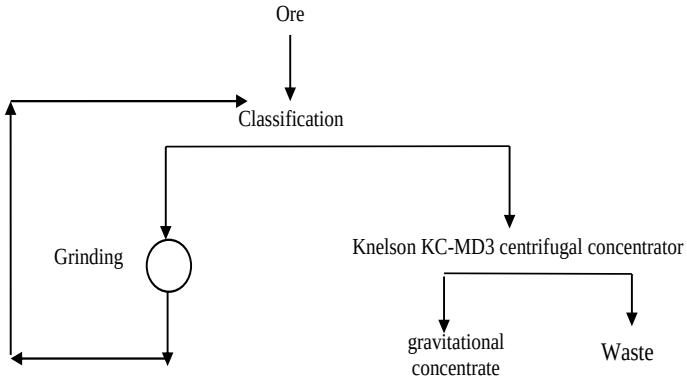


Figure-4: Experimental flow sheet for the Knelson KC-MD3 centrifugal-concentration tests.

Chemical analysis and performance indices: Gravity and flotation products were analyzed for valuable components by atomic-absorption spectrometry using a Perkin Elmer instrument. The available experimental record does not specify the instrument model, calibration protocol, analytical detection limits, replicate count, or analytical uncertainty; these items require confirmation from the original laboratory records before formal journal submission.

Product yield (γ_i) and component recovery (ε_i) were evaluated from mass and grade data using the standard relationships:

$$\text{Yield, } \gamma_i\ (\%) = \frac{m_i}{m_f} \times 100$$

$$\text{Recovery, } \varepsilon_i\ (\%) = \frac{\gamma_i \times \beta_i}{\alpha}$$

where m_i is the mass of product i, m_f is the feed mass, β_i is the component grade in product i, and α is the corresponding feed grade. These relationships were also used to check the internal consistency of the reported mass and metal balances.

Screening-level environmental performance assessment: The environmental assessment used a gate-to-gate screening boundary covering gravity feed and gravity products. It did not include mining, grinding electricity, process-water production, flotation reagents, smelting, transport, or tailings-storage emissions. This boundary was selected because detailed, disaggregated primary inventory data are essential for credible life-cycle interpretation of beneficiation operations[1-3]. The reported indicators must therefore be interpreted as resource-efficiency and tailings-prevention proxies, not as measured reductions in energy use, water use, toxicity, or greenhouse-gas emissions.

Four indicators were calculated for the best tested condition of each device: i. concentrate mass pull, equal to concentrate yield; ii. Au and Ag recovery to the pre-flotation concentrate; iii. upgrade ratio, defined as concentrate grade divided by feed grade and equivalently as component recovery divided by mass pull when both are expressed as percentages; and iv copper preservation, calculated as 100 minus Cu recovery to the gravity concentrate.

The proportions of Au and Ag remaining in the downstream stream were calculated as 100 minus their respective gravity recoveries. Lower mass pull combined with high precious-metal recovery and high copper preservation was treated as the preferred screening response.

Results and Discussion

Grinding response and flotation-related performance: The proportion of material finer than 0.074 mm increased from 8.94% in the initial sample to 45.7% after 10 min, 70.3% after 20 min, and 85.1% after 30 min of grinding (Table-1; Figure-2). Increasing the -0.074 mm fraction from 57% to 70% increased Cu recovery in flotation from 83.79% to 88.73%, while further grinding to 80% produced little additional improvement.

On this basis, approximately 70% passing 0.074 mm was the highest-performing tested grind level for Cu recovery within the reported series.

At this grind level, the bulk flotation concentrate yield was 7.76%. The concentrate assayed 4.77% Cu at 88.73% Cu recovery, 8.33g/t Au at 77.80% Au recovery, and 0.040% Mo at 82.61% Mo recovery. Because the complete flotation table for the 57-80% grind series is not available in the archived dataset, the intermediate 60% and 65% responses and the exact 80% recovery cannot be independently reconstructed.

Table-2: Results of the 30-KS laboratory shaking-table tests.

Product	Yield, %	Au grade, g/t	Ag grade, g/t	Cu grade, %	Au recovery, %	Ag recovery, %	Cu recovery, %	Frequency / amplitude
Gravity concentrate	1.10	8.86	52.18	0.11	19.30	22.60	0.33	100 min⁻¹ / 8 mm
Middling	5.63	1.17	8.25	0.01	13.10	18.30	0.21	
Gravity tailings	93.27	0.36	1.60	0.39	67.60	59.10	99.46	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	
Gravity concentrate	1.20	9.22	52.00	0.14	21.91	24.60	0.45	110 min⁻¹ / 10 mm
Middling	6.40	1.15	7.80	0.02	14.60	19.70	0.35	
Gravity tailings	92.40	0.34	1.53	0.40	63.49	55.70	99.20	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	
Gravity concentrate	1.05	7.80	46.50	0.09	16.20	19.20	0.26	120 min⁻¹ / 12 mm
Middling	5.20	1.22	8.30	0.01	12.60	17.00	0.14	
Gravity tailings	93.75	0.38	1.73	0.39	71.20	63.80	99.60	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	

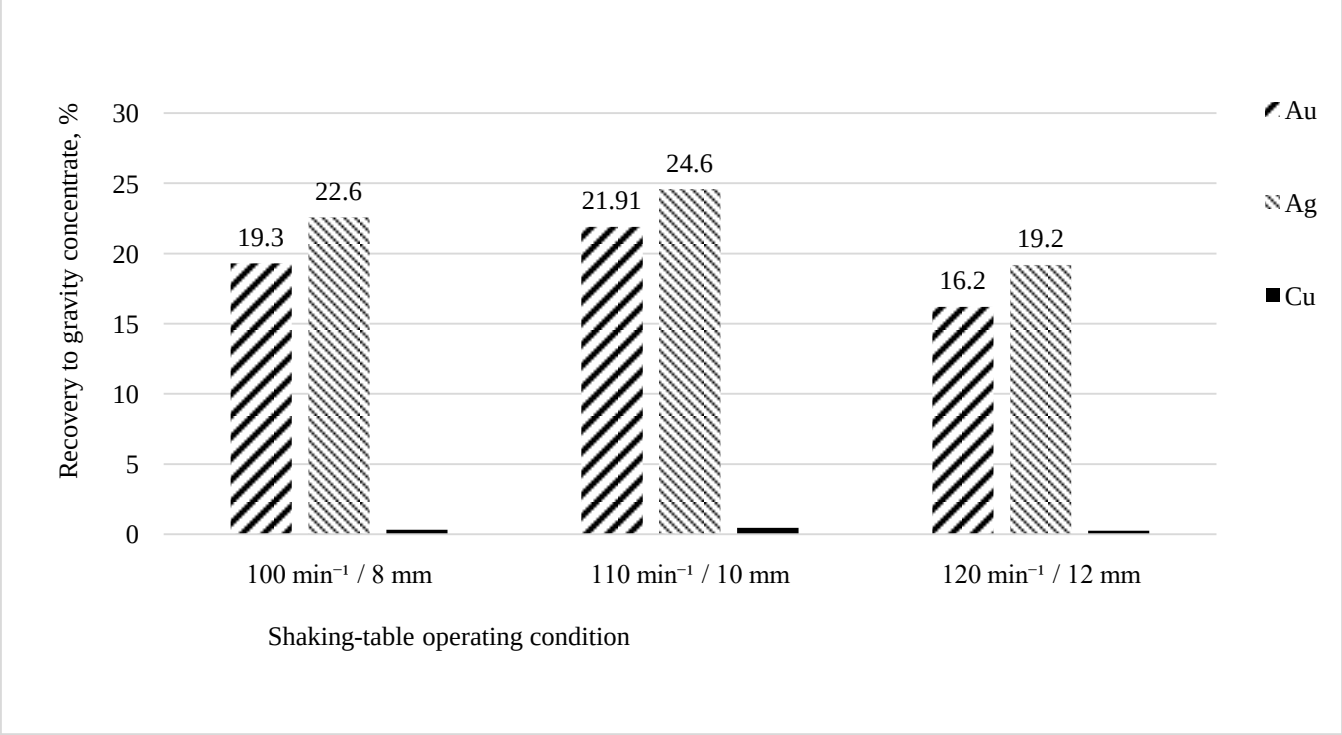


Figure-5: Recovery of Au, Ag, and Cu to the shaking-table gravity concentrate under the three tested operating conditions.

The 110 min⁻¹/10 mm condition produced the highest observed gravity-concentrate recoveries of Au (21.91%) and Ag (24.60%) among the shaking-table tests, at a concentrate yield of 1.20%. The corresponding concentrate grades were 9.22 g/t Au, 52.00 g/t Ag, and 0.14% Cu. Au recovery decreased to 19.30% at 100 min⁻¹/8 mm and to 16.20% at 120 min⁻¹/12 mm. Cu recovery to the gravity concentrate remained low (0.26-0.45 %), while 99.20-99.60% of the reported Cu recovery remained in gravity tailings.

The Table-3 values for the 110 min⁻¹/10 mm test are internally more consistent than an alternative narrative value of 10.9 g/t Au and 40.5% combined Au recovery. Accordingly, the Table-2 values (9.22 g/t Au in concentrate and 36.51% combined Au recovery to concentrate plus middling) are retained for quantitative interpretation.

Knelson centrifugal-concentration tests: Within the tested Knelson range, 65 G produced the highest observed Au grade and Au recovery in the gravity concentrate. The 0.92% concentrate assayed 13.69 g/t Au, 57.43g/t Ag, and 0.29% Cu, corresponding to recoveries of 24.94%, 20.80%, and 0.73%, respectively. Au recovery was 22.83% at 55 G and 22.40% at 75 G. Cu recovery to concentrate remained below 1% in all Knelson tests. Because of the balance inconsistency noted for the 55 G Ag value and the 75 G yield/Au balance, those specific values are not used for balance-sensitive conclusions.

Table-3: Results of the Knelson KC-MD3 centrifugal-concentration tests.

Product	Yield %	Au grade g/t	Ag grade g/t	Cu grade, %	Au recovery %	Ag recovery %	Cu recovery %	Acceleration
Concentrate	0.89	12.95	8.23	0.27	22.83	19.80	0.66	55 G
Tailings	99.08	0.39	2.06	0.37	77.17	80.20	99.34	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	
Concentrate	0.92	13.69	57.43	0.29	24.94	20.80	0.73	65 G
Tailings	99.08	0.38	2.03	0.37	75.06	79.20	99.27	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	
Concentrate	1.12	10.10	43.62	0.20	22.40	19.25	0.61	75 G
Tailings	99.08	0.38	2.07	0.37	75.06	80.75	99.39	
Feed	100.00	0.505	2.54	0.37	100.00	100.00	100.00	

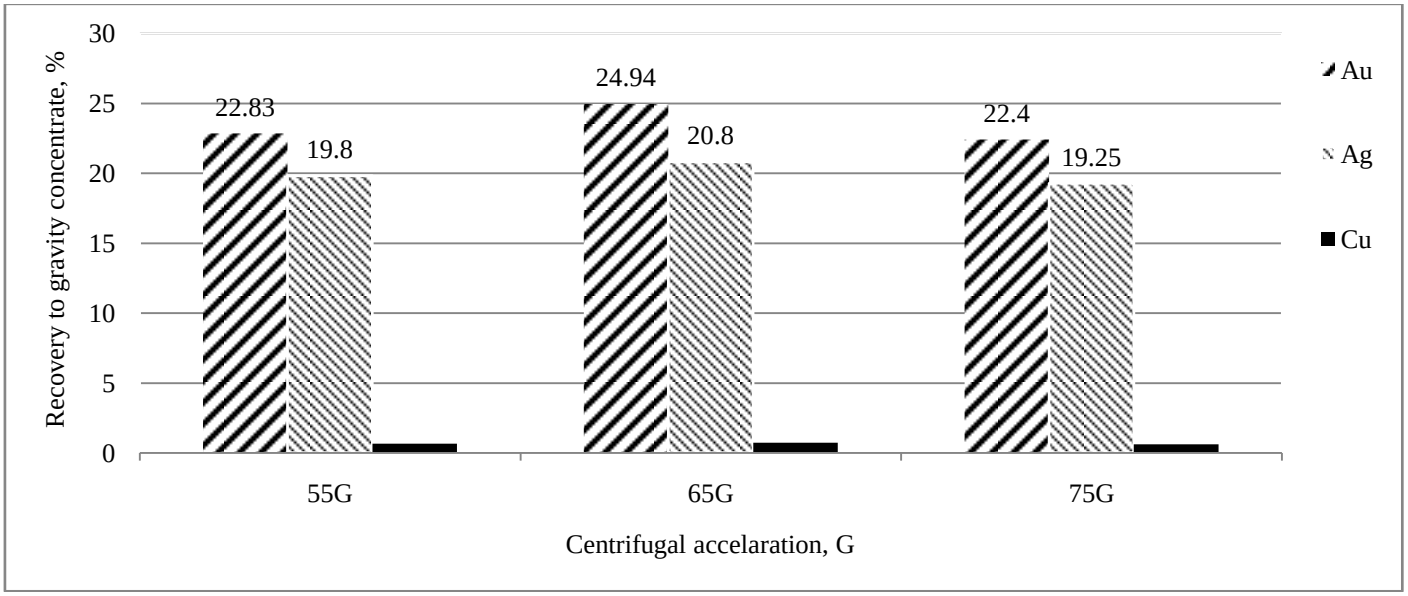


Figure-6: Recovery of Au, Ag, and Cu to the Knelson gravity concentrate at 55, 65, and 75 G.

Comparative performance: Comparison of the best tested conditions shows a device-dependent trade-off. Relative to the 110 min^{-1}/10 mm shaking-table condition, the 65 G Knelson condition increased Au recovery by 3.03 percentage points (24.94% versus 21.91 %) and Au concentrate grade by 4.47 g/t (13.69 versus 9.22 g/t). The Knelson product also had a higher Ag grade (57.43 versus 52.00 g/t), but its Ag recovery was 3.80 percentage points lower (20.80% versus 24.60%). Thus, the Knelson condition favored Au upgrading, whereas the shaking table recovered a larger fraction of Ag. In both cases, less than 1% of Cu reported to the gravity concentrate.

Environmental performance indicators: The best shaking-table test captured 21.91% of Au and 24.60% of Ag in 1.20% of the feed mass. Its Au and Ag upgrade ratios were 18.3 and 20.5, respectively, and 99.55% of Cu remained available for downstream flotation. The best Knelson test captured 24.94% of Au and 20.80% of Ag in 0.92% of the feed mass, with upgrade ratios of 27.1 for Au and 22.6 for Ag; 99.27% of Cu remained in the downstream stream. These values show that the environmental relevance of the gravity stage arises from selective resource recovery at very low mass pull rather than from bulk waste rejection.

If the recovered gravity concentrate is processed in a controlled product stream, the operation can prevent the captured gravity-responsive Au and Ag from following the bulk ore toward final tailings. However, the data do not demonstrate a reduction in total tailings mass because 98.80-99.08% of the feed remains in the downstream stream. They also do not demonstrate lower flotation energy, water, or reagent demand because the gravity tailings were not tested in a complete comparative flotation campaign.

Environmental Discussion: The result shows how a physical pre-concentration step may improve the environmental performance of mineral beneficiation. Beneficiation and flotation can contribute materially to energy demand, water scarcity, reagent-related toxicity, climate impacts, and resource use[1-3]. Recovering 20.80-24.94% of a gravity-responsive precious-metal component into less than 1.20% of the feed mass improves resource capture before waste disposal, while copper preservation above 99% limits interference with the principal Cu circuit. This is a measurable resource-efficiency benefit, although it is not yet an inventory-based environmental impact reduction.

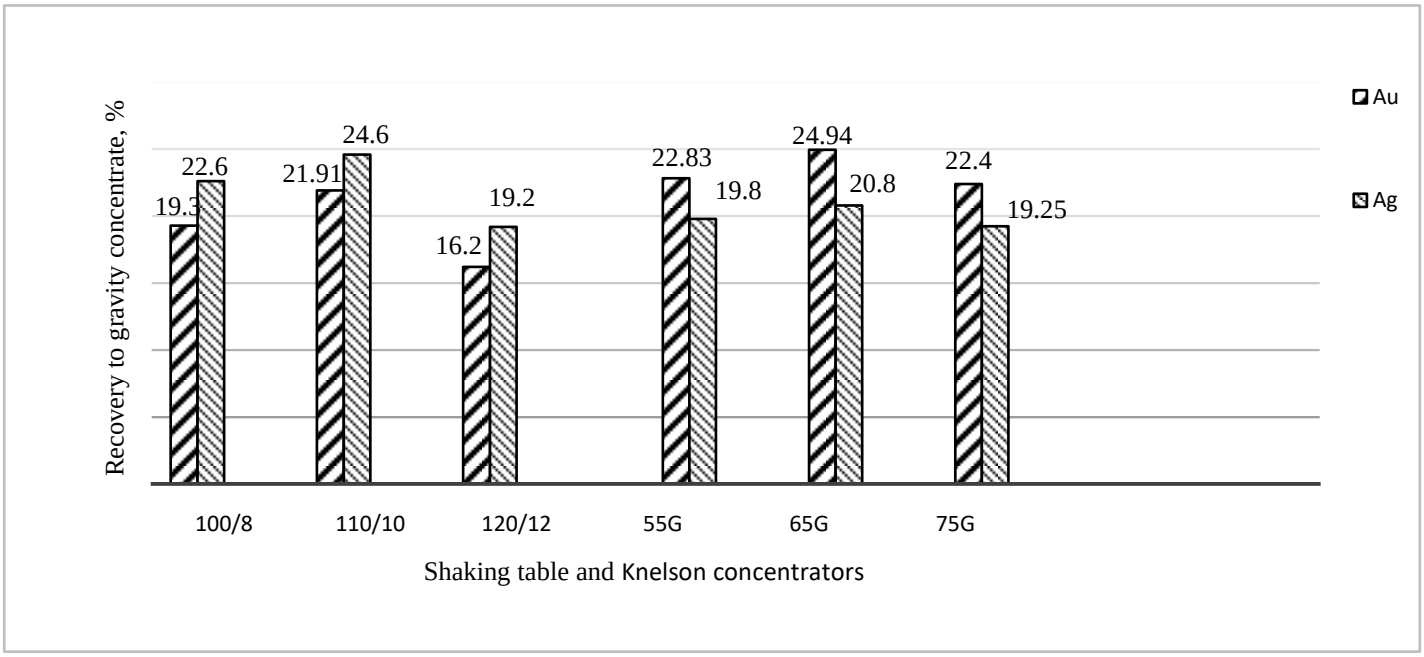


Figure-7: Comparative Au and Ag recoveries to gravity concentrate. Shaking-table and Knelson operating conditions are shown as separate groups to avoid implying a continuous physical trend between the two devices.

Table-4: Screening indicators for the best tested condition of each gravity device. Source: Authors' laboratory dataset.

Device / condition	Mass pull, %	Au recovery, %	Ag recovery, %	Au upgrade ratio	Ag upgrade ratio	Cu preserved, %
30-KS table, 110 min-1 / 10 mm	1.20	21.91	24.60	18.3	20.5	99.55
Knelson KC-MD3, 65 G	0.92	24.94	20.80	27.1	22.6	99.27

The distinction is important because life-cycle studies of copper and gold production identify electricity supply, ore grade, on-site emissions, reagent use, and tailings management as major determinants of environmental performance[1-5]. A gravity device also consumes electricity and water; therefore, the preferred device cannot be selected environmentally from recovery data alone. The Knelson test gave higher Au recovery and a lower mass pull, whereas the shaking table gave higher Ag recovery. A full comparison requires measured kWh per tonne, make-up water per tonne, recirculated-water fraction, reagent consumption in subsequent flotation, concentrate-treatment requirements, and the chemical and acid-generation characteristics of final tailings.

The shaking-table results indicate a response maximum at the intermediate tested frequency/amplitude pair. On a shaking table, separation is governed by the combined effects of stratification, differential particle transport, deck motion, and wash-water flow[7-9]. The lower 100 min^{-1}/8 mm setting may have provided insufficient differential transport for the densest gravity-responsive particles, whereas the 120 min^{-1}/12 mm setting may have increased bed disturbance and hydraulic transport. These mechanisms are process-based interpretations rather than directly measured phenomena because particle trajectories and bed hydrodynamics were not quantified.

The Knelson results similarly show the highest Au response at the intermediate tested acceleration of 65 G. Knelson performance depends jointly on centrifugal acceleration and fluidized-bed behavior[10-14]. Increasing acceleration strengthens the driving force for dense-particle retention, but excessive acceleration under a fixed or narrow fluidization-water range can alter bed packing, interstitial flow, and particle entrainment. The modest decrease in Au recovery at 75 G may therefore reflect a shift in the balance between retention and fluidization. Confirmation would require experiments in which acceleration and fluidization-water rate are varied independently.

The observed Au recoveries are consistent with the broader understanding that laboratory gravity performance depends strongly on liberation, particle morphology, and the amount of gravity-recoverable gold available to the separator[9,15,17,19]. The present study did not include quantitative liberation analysis, SEM-based mineralogy, or a standard GRG test; consequently, the recovered Au and Ag fractions should be described as gravity-responsive rather than definitively "free" or fully liberated. Mineralogical characterization is recommended in future work because it can distinguish true density-controlled upgrading from responses governed by mineral association and particle-size effects[19].

The very low Cu recovery to gravity concentrate is technologically important. Kalmakyr is a porphyry Cu–Au–Mo system in which copper is principally associated with sulfide mineralization[6]. Across the tested gravity conditions, the great majority of Cu remained in gravity tailings, indicating that the gravity stage preferentially removed only a small mass fraction while preserving the copper-bearing stream. This behavior is compatible with earlier work showing that centrifugal gravity recovery can be integrated with copper flotation without requiring the gravity stage to serve as the principal Cu-recovery operation[18]. However, the present experiments did not include a complete gravity-tailings flotation campaign, so an improvement in downstream flotation performance cannot be claimed directly.

The comparison also shows that "best" performance is metal- and objective-specific. The 65 G Knelson test yielded the highest observed Au grade and Au recovery, while the 110 min^{-1}/10 mm shaking-table test achieved higher Ag recovery. Selection of a preferred device therefore requires a defined circuit objective and should ultimately consider concentrate cleaning, downstream flotation response, water demand, throughput, operating cost, and product handling. These factors were outside the scope of the current laboratory study.

The grinding results provide a complementary process observation. Increasing the -0.074 mm fraction from 57% to approximately 70% increased Cu flotation recovery from 83.79% to 88.73%, whereas additional grinding to 80% produced little reported benefit. This trend is consistent with selecting the minimum comminution intensity needed to achieve useful liberation while avoiding unnecessary energy consumption and excessive fines generation; particle size and morphology are also known to influence gravity and flotation response[8,14,17]. Because the full five-point flotation dataset is not available in the archived record, the 70% target should be interpreted as the highest-performing reported grind level rather than a statistically optimized value.

Study limitations include the absence of replicate-test variability, incomplete instrument details, lack of quantitative liberation analysis, a missing full flotation grind-series table, and two unresolved Knelson balance inconsistencies. Environmental limitations are equally important: no electricity meters, water balance, reagent inventory, tailings leach ability, acid-base accounting, or life-cycle impact assessment were included. Before an industrial environmental claim is made, paired baseline and gravity-assisted flotation campaigns should quantify energy, water, reagents, final recovery, tailings mass, dissolved metals, and acid-generation potential per tonne of ore. Replicate tests and uncertainty analysis should then be used to determine whether any apparent environmental improvement is statistically and practically significant.

Conclusion

Pre-flotation gravity concentration recovered approximately one-fifth to one-quarter of the gravity-responsive Au-Ag inventory into only 0.92-1.20% of the feed mass while preserving more than 99% of Cu for downstream flotation. This

is a direct resource-efficiency benefit and may reduce valuable-metal loading to final tailings.

For the 30-KS shaking table, 110 min^{-1} at 10 mm amplitude was the highest-performing tested condition. A 1.20% gravity concentrate assayed 9.22g/t Au and 52.00g/t Ag, with recoveries of 21.91% Au and 24.60% Ag.

For the Knelson KC-MD3, 65 G gave the highest observed Au response. A 0.92% gravity concentrate contained 13.69g/t Au and 57.43g/t Ag, wi+th recoveries of 24.94% Au and 20.80% Ag.

Relative to the best shaking-table test, the 65 G Knelson condition increased Au recovery by 3.03 percentage points and Au grade by 4.47g/t, whereas the shaking table recovered 3.80 percentage points more Ag. Device selection therefore depends on the target-metal objective.

The present evidence supports an environmental screening conclusion, not a complete claim of reduced impact. Industrial validation must measure electricity, water, flotation reagents, final tailings chemistry, and life-cycle impacts for baseline and gravity-assisted flow sheets.

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