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Comprehensive Utilization of Tailings in Quartz Vein-Hosted Gold Deposits

Liuhui Chen, Qian Li * and Tao Jiang

School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China
* Correspondence: csuliqian@126.com; Tel.: +86-731-8883-0547

Abstract: The aim of this study was to develop a comprehensive technology for the utilization of tailings from quartz vein-hosted gold deposits. We investigated the recovery potential and separation process for gold, feldspar, and quartz from tailings samples collected from the Jinqu gold mine in Henan province, China. The sequence of the principal flowsheet of the comprehensive utilization of gold, feldspar, and quartz from the tailings samples was determined according to the process mineralogy and corresponding experiments. The residual gold in the tailings was extracted, and both feldspar and quartz concentrates were recovered according to the flowsheet of selective desliming, flotation of gold-bearing sulfide ore, removal of iron-containing impurities, flotation separation of feldspar, and purification of quartz. The quartz concentrate met China's industrial standard for raw-material quartz sand for producing high-grade glass, such as cover glass for touch electronics and TFT LCD liquid crystal substrate glass. The feldspar concentrate also met China's ceramic industry standards. The established process provides an efficient way for recovering the main valuable minerals in tailings from quartz vein-hosted gold deposits. Moreover, this study demonstrates the synthetic recovery of the same type of gold tailings.

Keywords: comprehensive utilization; gold tailings; beneficiation; quartz; feldspar

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1. Introduction

Gold is not only a currency or an asset, but also a valued commodity in economic circulation and international financial markets. The increasing demand for gold is evident in industries such as the jewelry industry, as well as the banking and technology sectors. The World Gold Council reported that approximately 190,000 tons of gold has been mined since 1950, and most high-grade ore deposits have already been depleted [1,2]. The grade of gold ore was projected to fall from 4 g/t to 3 g/t in 2012, and to 1 g/t in 2020 [3]. However, the demand for gold remains on the rise, because of the growing demand for electronic products, such as computers and smartphones [4,5], creating the need to mine more gold, which in turn produces more tailings.

It is estimated that over 24.5 million tons of gold tailings are produced annually in China [6]. According to the China Gold Association, the domestic gold output in 2021 was 328.98 tons, of which 258.09 tons were generated from gold mining [7]. Currently, a highly effective way to utilize gold tailings is to use them to backfill the mine, which comprises valuable land resources [8]. This method pollutes the atmosphere, the earth's surface, and surrounding water in the mining area, and it inhibits plant growth in the environment [9–12]. Community health is also threatened by heavy metal ions and the diffusion of residual mineral dressing agents in the tailings [13–16]. Therefore, gold mining companies invest heavily in constructing and maintaining tailing ponds [17]. Tailings are fundamentally a non-economically valuable material because they are a by-product of the gold ore concentration processes and constitute mining waste. Nevertheless, tailings from mined gold contain abundant gangue minerals (e.g., quartz, feldspar, mica, calcite) and some valuable renewable elements, such as potassium, iron, and aluminum, which must be further processed and utilized [18–20]. Quartz and feldspar are important industrial raw materials with a wide range of uses.

The recovery of gold from tailings consists of physical methods, including gravity separation, flotation, and magnetic separation processes, as well as chemical methods, such as cyanidation and heap leaching [16]. Different methods should be adopted according to different tailing components and recovery objects [21,22]. Many studies have explored the recovery of valuable metals and metalloids from tailings. Altinkaya et al. proposed a new approach for recovering trace metals from sulfide flotation tailings in cupric chloride solutions, and the recovery of Cu, Ni, Zn, Co, Fe, and Au was greater than 75% [23]. Liu et al. investigated the effect of magnetic roasting on the recovery of valuable metals [24] and found that the leaching rate of gold reached 46.1% while the magnetic susceptibility of iron exceeded 86.3%. Flotation separation of non-metallic minerals is also a widely used method. Zhijie et al. used sodium petroleum sulfonate (SPS) as a collector with sodium hexametaphosphate (SHMP) as a depressant to separate fluorite from barite; the result indicates that barite was selectively separated from fluorite by the reagent scheme of 1.28×10^{-6} mol L^{-1} of SHMP and 0.3 g L^{-1} of SPS at pH 11 [25]. Ruiqi et al. synthesized a new collector, N-{3-[(2-propylheptyl)oxy]propyl}propane-1, 3-diamine, that is suitable for the reverse flotation of spodumene coarse concentrate [26].

Studies have demonstrated the feasibility of utilizing tailings as pigments for paints, cement mortars, concrete-making materials, bricks, and ceramic materials [27–32]. Moreover, utilizing tailings could benefit society and reduce environmental hazards. Hence, researchers are increasingly focusing on establishing cost-effective technologies for the optimum utilization of tailings. However, the recovery and complete utilization of some valuable elements from the gold-mined tailings of quartz vein-hosted gold deposits is rarely investigated. It is crucial to develop new methods for the synthetical recovery of gold as well as quartz and feldspar from gold tailings.

Quartz vein-hosted gold deposits are a major gold deposit type [33], which is rich in recyclable quartz and feldspar, but not residual gold. The aim of this study was to establish a standard procedure for the high-value utilization of tailings from quartz vein-hosted gold deposits. A systematic experimental study of the comprehensive utilization of tailings was conducted through the technological mineralogy of tailings from quartz vein-hosted gold deposits collected from the Jinqu gold mine in Henan province, China.

2. Experiments

2.1. Materials and Basic Characteristics

2.1.1. Materials

Henan Jinqu Gold Co., Ltd. is a gold mining enterprise managed by Zhongjin Gold Co., Ltd. and located in Lingbao City, Henan province, China. The mining area selected for the experiment was in the Xiaoqinling gold field, whose production scale is 1100 t/d. The tailing pond in this field is a fourth-class pond commissioned in 2006, and the final height of the stacking dam elevation design is below 5 m, while the remaining service life is 1.5 years. The materials used in this study included gold tailings (MT) that were logically collected from four different spots at 100-m intervals for an adequate representation of the area.

Each sample was collected independently at a different location and depth of the pond to represent different gold tailings from different areas. Approximately 45 kg, equivalent to 10 tailings samples, were collected. The samples were taken to the laboratory, dried naturally for 48 h, mixed thoroughly, and separated into several samples for further analyses and experimentation. The samples were then subjected to chemical, XRD, particle size, and mineralogy characteristic analyses.

2.1.2. Basic Sample Characteristics

The chemical compositions of the gold tailings samples are presented in Table 1, and the gold distribution is presented in Table 2. Table 1 shows that the sample component with the highest composition (72.91%) was SiO_2, whereas the K_2O and Au contents accounted for 4.17% and 0.2 g/t of the samples, respectively, indicating the potentially high economic value of the samples. The recovery of gold and other products such as quartz can provide raw materials for the subsequent extraction of gold and the production of high-quality glass while reducing the generation of acidic wastewater in the area. The gold tailings samples mainly comprised sulfide, of which the gold distribution was up to 57.14%, as presented in Table 2. The distribution of gold in iron-containing oxides, such as hematite and limonite, was 19.05%. The former is easy to recover through flotation, whereas the latter is difficult to recover even using recent technology.

Table 1. Chemical composition of tailings samples from quartz vein-hosted gold deposits (mass fraction, %).

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO	S	TiO_2	CuO	NiO	MnO	WO_3	Pb	Zn	Au *(g/t)
Content	72.91	11.50	4.16	4.17	1.21	4.04	1.11	0.12	0.24	0.014	0.018	0.010	0.025	0.005	0.007	0.20

* Unit g/t.

Table 2. Gold phase distribution of tailings samples from quartz vein-hosted gold deposits (mass fraction, %).

Phase	Elemental Gold	Gold in Sulfide	Gold in Hematite, Limonite	Gold in Others	Total Gold
Content	0.03	0.12	0.04	0.02	0.21
Distribution	14.29	57.14	19.05	9.52	100.00

The particle size of the gold tailings samples was analyzed by hydraulic classification, and Table 3 presents the particle size distribution. The particles whose size fraction was +0.074 mm achieved a distribution of over 37.68%.

Table 3. Particle size distribution of gold tailings samples.

Particle Size (mm)	Distribution (%)	Cumulative Distribution (%)
+0.154	16.75	16.75
−0.154 + 0.074	20.93	37.68
−0.074 + 0.045	28.61	66.29
−0.045 + 0.038	13.47	79.76
−0.038 + 0.019	6.35	86.11
−0.019	13.89	100.00
Total	100.00	/

2.2. Separation Principles and Experimental Methods

2.2.1. Recovery Process

According to the results of the basic characteristics of the samples, the gold in the tailings samples was notably abundant in sulfide ore and iron-containing oxides. Thus, the recovery process of sulfide and oxides, such as hematite and limonite, from the tailings was directly incorporated into the recovery process implemented in this study. Quartz in tailings is mainly found as coarse particles. The particle sizes of potassium feldspar are evenly distributed, and the particle sizes of hematite and chlorite impurities are mostly distributed as −0.038 mm, with an obvious influence on product quality during quartz and potassium feldspar recovery. The separation sequence was determined according to the basic characteristics of the samples, and Figure 1 illustrates the flowsheet of gold, quartz, and feldspar recovery from the gold tailings.

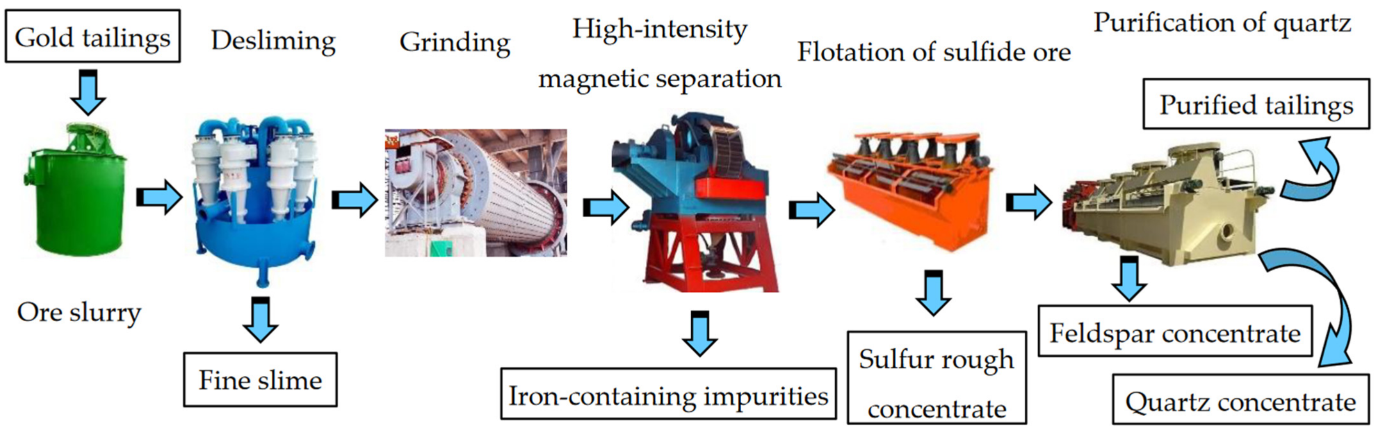

Figure 1. Flowsheet of gold, quartz, and feldspar recovery from gold tailings samples.

2.2.2. Experimental Methods and Procedures

The separation and recovery process of gold, quartz, and feldspar from gold tailings samples is complex; thus, the main separation process was divided into three steps.

The first step was desliming by classification to remove particles with fine sizes from the samples. The tailings samples were prepared and mixed thoroughly; subsequently, the pulp was pumped tangentially into a hydrocyclone (FX250, Zhongyuan Mechanical Equipment Co., Ltd., Xinxiang, China) with a diameter of 250 mm by a slurry pump at a pressure ranging from 0.05 to 0.4 MPa. The pressure was set to 0.15 MPa to ensure separation efficiency and avoid mechanical loss, and the pulp density was set between 35% and 40%. Subsequently, the particles were separated into underflow and overflow types. After ensuring a stable hydrocyclone operation, the underflow and overflow particles were removed and filtered. The underflow and overflow particles were dried separately using a standard thermostatic drying oven for subsequent chemical analyses.

The second step was a wet high-intensity magnetic separation process performed to eliminate magnetic impurities, including hematite, limonite, and superfine magnetite intergrowth particles. A wet high-intensity magnetic separator (XCSQ-50 × 70, Wuhan Hengle Mineral Engineering Equipment Co., Ltd., Wuhan, China) was used to separate weakly magnetic minerals. The magnetic field strength of the laboratory scale machine was set to 0–2.3 T, and the processing capacity was 4–5 kg/h. The samples were prepared by mixing 3 kg of the gold tailings with water and feeding them to the apparatus. The magnetic and non-magnetic materials were transported by the water and then collected in separate containers. The strength of the magnetic fields was adjusted from 0.8 T to 1.0 T and then to 1.3 T to obtain the best separation results. After separation, both samples were dried with a standard thermostatic drying oven and subsequently subjected to chemical analysis.

At the third step, different flotation separation experiments were performed to eliminate sulfide impurities and other nonmetallic-oxide impurities. These experiments were performed using a self-aeration XFD-2 L flotation machine (GTK Lab Cel, Outotec Osakeyhtiö, Espoo, Finland). After the flotation machine was washed with clean water, the tailings samples were put into the flotation cell, and the surface level was readjusted by adding water. The cells were filled with air, and the reagents were added vertically and in sequence: sodium carbonate (375 g/t), copper sulfate (300 g/t), butyl xanthate (45 g/t), and No. 2 flotation oil (ROH) (30 g/t). The reagents were allowed to act on the samples for intervals of 3 min, 2 min, and 1 min. Air filling was then stopped while stirring began.

Subsequently, regulator, collector, and foaming agents were separately added into the pulp and were stirred separately for a fixed time (1–3 min), after which aerated flotation was performed for a fixed time. The obtained concentrate and tailings were dehydrated, dried, and weighed to determine the desired content of the component from which the recovery rate would be calculated.

2.3. Analysis and Detection Methods

The chemical composition and mineralogy of the samples were analyzed using a mineral liberation analyzer (MLA) (MLA 150, FEI, Heidelberg, Germany). The mineralogy of the samples was determined using an X-ray powder diffraction machine (Advance D8, Bruker, Billerica, MA, USA) with a Cu–Kα radiation range of $5^\circ < 2\theta < 80^\circ$, a step size of 0.02°, and a scan rate of 5°/min. The chemical phase composition analysis of the gold tailings samples comprised iodine-bromo-perchloric acid-hydrochloric acid leaching methods [31–33]. The particle size of the separated concentrates and gold tailings samples was determined using a set of standard Tyler sieves with mesh sizes of 100 to 600 (0.148–0.025 mm). The liberation degree and occurrence characteristics of the particles were observed using a scanning electron microscope (VEGA3-SBH, TESCAN Brno, s.r.o, Brno, Czech Republic). Furthermore, the yield of each grade sample was weighed and calculated, and the chemical compositions were analyzed. The samples of different grades were polished and observed under an optical microscope to determine their mineral liberation degrees. The viscosity of the glass samples from Silbelco and the tailings was measured with a glass SRV-1600 high-temperature rotary viscometer, and the thermal expansion coefficient of the samples was determined with a horizontal dilatometer (DIL 402 Expedis Classic, Netzsch, Selb, Germany).

3. Results and Discussion

3.1. Characterization of Gold Tailings

3.1.1. Mineralogical Composition

Figure 2 illustrates the XRD pattern of the gold tailings samples. The diffraction peaks of quartz, K-feldspar, plagioclase, and sanidine were sharp and intense, indicating their highly crystalline nature. The mineral contents of the gold tailings are presented in Table 4.

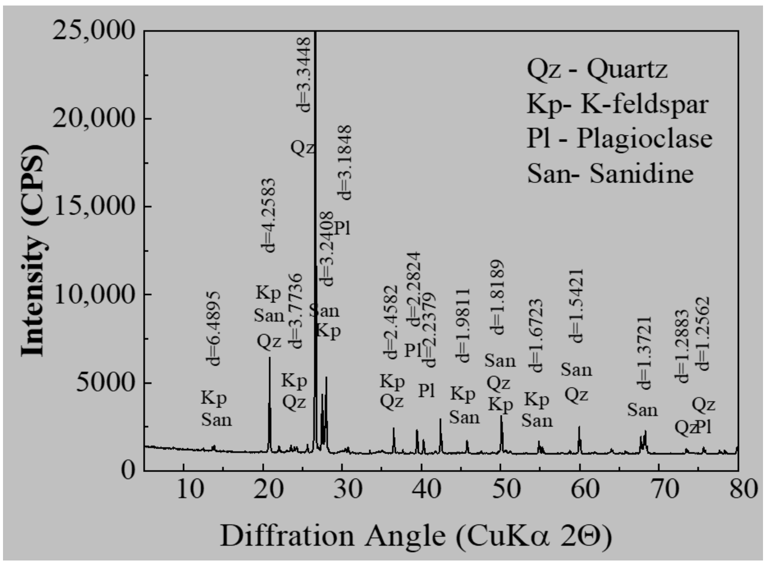

Figure 2. XRD pattern of quartz vein-hosted gold tailings samples.

Table 4. Mineral compositions of the gold tailings (mass fraction, %).

Minerals	Quartz	K-Feldspar	Plagioclase	Sericite	Calcite	Magnetite, Hematite	Mica	Chlorite	Limonite, Lmenite	Magnetite, Pyrite	Amphiboles	Rutile	Chalcopyrite	Others
Content	40.3	32.8	9.6	7.2	5.1	1.0	1.1	0.7	0.5	0.4	0.4	0.3	0.1	0.5

The tailings samples had a complex mineralogical composition. The content of metallic minerals was approximately 2.0%, comprising magnetite, pyrite, pyrrhotite, ilmenite, hematite, rutile, chalcopyrite, and limonite. The content of the transparent minerals was approximately 98.0%, mainly comprising quartz, K-feldspar, plagioclase, calcite, and sericite.

Quartz and K-feldspar were the most abundant minerals in the gold tailings samples, accounting for 40.3% and 32.8%, respectively.

3.1.2. Mineralogical Characterization

The occurrence characteristics of the gold tailings samples were analyzed, and the results are shown in Figure 3. The quartz particles had smooth surfaces and irregular granular shapes; some of the particles were closely associated with K-feldspar and muscovite. Cleavages were observed in the irregular granular K-feldspar (Kfs), with a rich stripe structure, and the K-feldspar was partly metasomatized by calcite and associated with quartz. The dissemination sizes of the quartz, K-feldspar, and sericite were unevenly distributed in the ranges of 0.02–1.0 mm, 0.01–1.0 mm, and 0.002–0.1 mm, respectively. Pyrite (Py) also exhibited a cubic crystal cross-section, and part of the pyrite was strongly metasomatized by limonite, showing a residual structure. Magnetite (Mt) was associated with quartz and other minerals, partially replaced by hematite and pyrite.

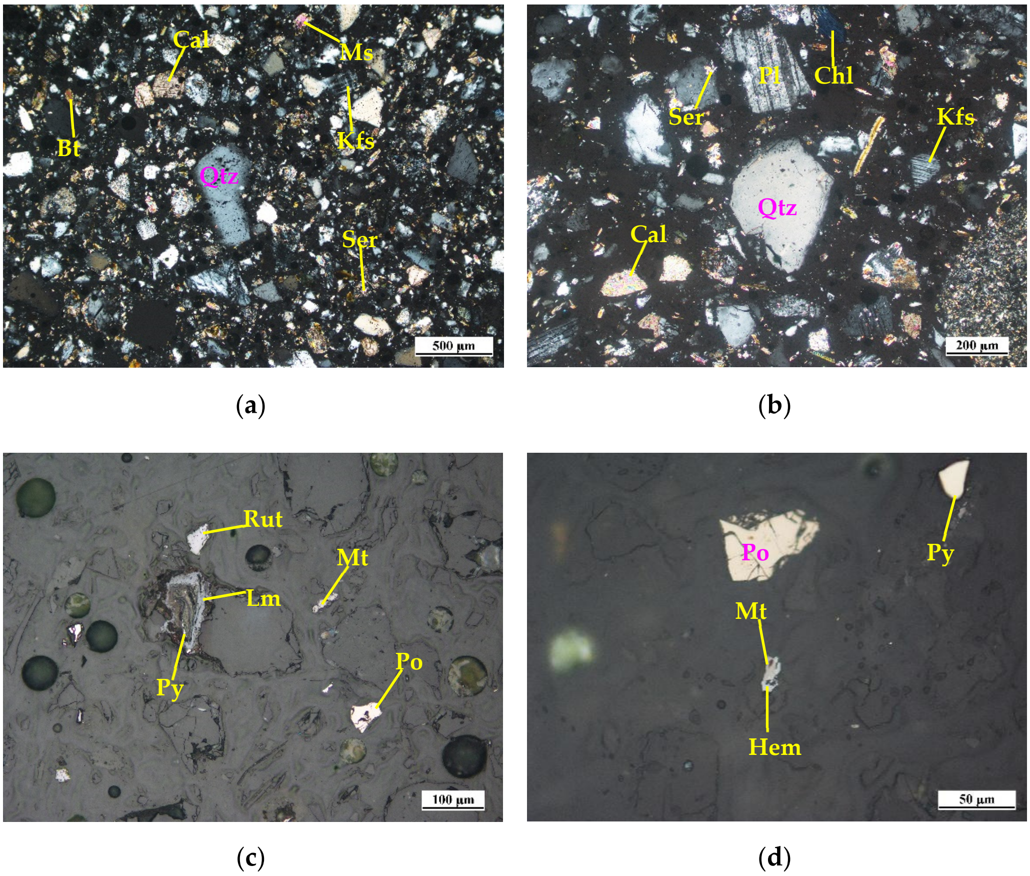

Figure 3. Microscopic photographs of minerals and embedding characteristics of tailings samples. (Qtz: Quartz; Kfs: K-feldspar; Cal: Calcite; Ser: Sericite; Bt: Biotite; Ms: Muscovite; Pl: Plagioclase; Chl: Chlorite; Mt: Magnetite; Py: Pyrite; Po: Pyrrhotite; Lm: Limonite; Rut: Rutile; Hem: Hematite). (**a**) Quartz (Qtz) particles with smooth and irregular surface; transmission light, perpendicular polarized light (+). (**b**) Irregular granular K-feldspar (Kfs) with cleavage and a rich stripe structure; transmission light, perpendicular polarized light (+). (**c**) Pyrite (Py) with cubic crystal cross-section characteristics and part of the pyrite strongly metasomatized by limonite, showing residual structure; reflect light. (**d**) Magnetite (Mt) associated with quartz and other minerals, partially replaced by hematite; reflect light.

3.1.3. Particle Size Distribution and Mineral Liberation Degree

The grades and distributions of gold in different particle sizes of the gold tailings samples are illustrated in Figure 4. As shown in Figure 4, the larger the particle size in the gold tailings, the higher the gold content, and the smaller the particle size, the lower the gold content. Thus, the gold content in the coarse grade of gold tailings is higher than that in the fine grade. The mineral compositions of samples of different sizes are presented in Figure 5. The particles whose sizes were +0.074 mm accounted for 37.68% (see Table 3), where the distribution of gold reached 49% (wt.%).

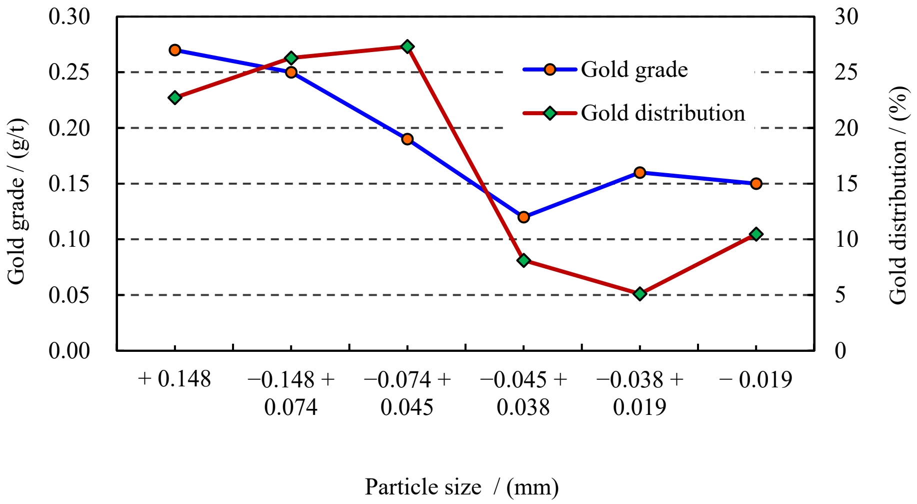

Figure 4. Particle size distributions of tailings samples and gold distribution depending on size.

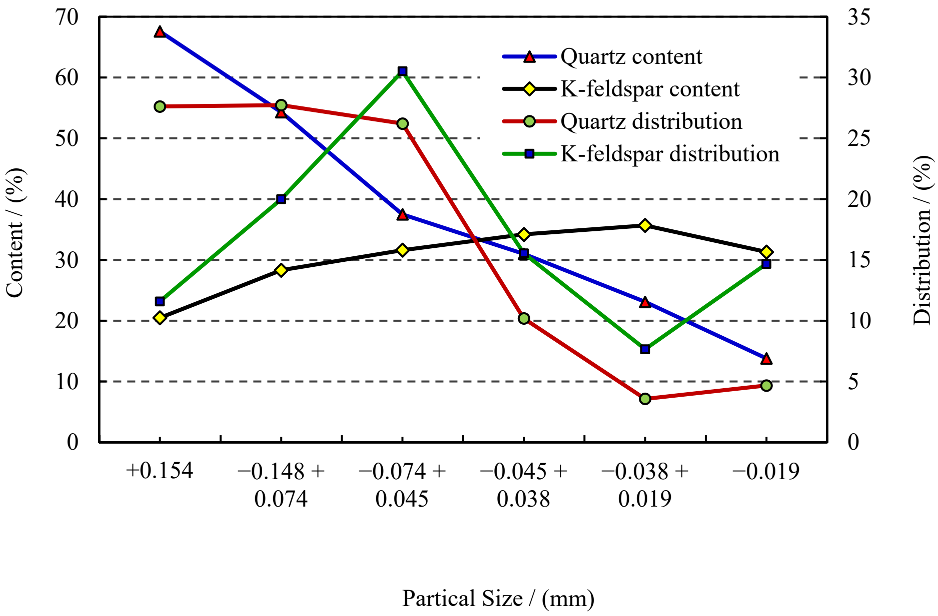

Figure 5. Main mineral composition in tailings samples with different particle sizes.

Figure 6 illustrates the liberation degree of the minerals in the samples with different particle sizes and shows that the occurrence state of gold in the samples was mainly encapsulation and interlocking. The distribution of quartz in the samples was 55%, indicating that quartz can be abundant depending on particle size because its surface is harder than that of other minerals. In samples with a size fraction of −0.074 mm, the main minerals were hematite, plagioclase, chlorite, and sericite. Sericite was abundant in samples with a size fraction of −0.03 mm.

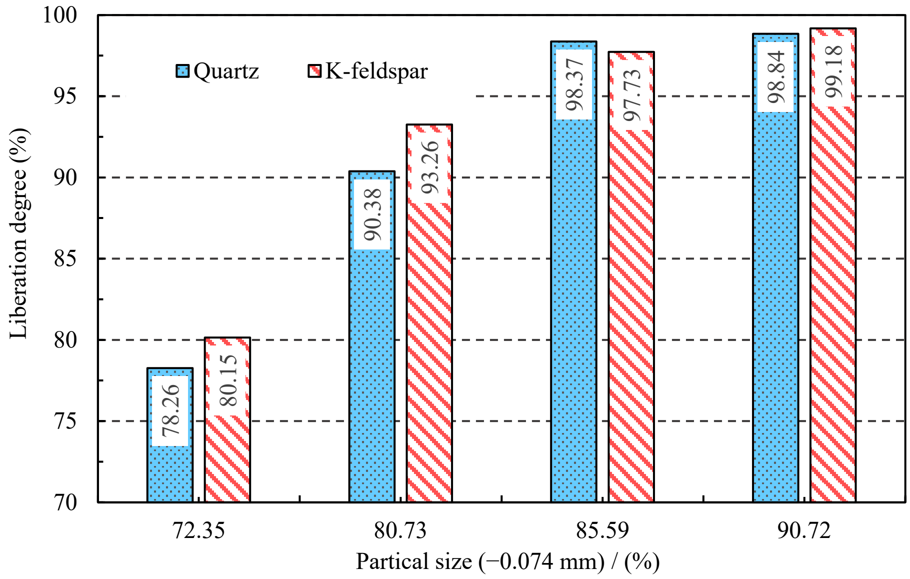

Figure 6. Liberation degree of quartz and K-feldspar in samples with different particle sizes.

3.2. Desliming through Hydrocyclone Classification

By analyzing the mineralogical properties of the samples and investigating the components of the gold tailings samples, we found that the main minerals in the samples with a particle size of −0.037 mm were sericite, carbonate, and iron. Fine slime in the tailings affects the recovery of quartz and feldspar [34]; thus, the slime should be removed beforehand. Table 5 summarizes the results of the desliming procedure. The table shows that Au and SiO_2 were prominently enriched in the desilting process, indicating that the desliming procedure can not only avoid the adverse effect of the fine slime but can also be effective for the subsequent recovery of quartz and gold.

Table 5. Desliming results (mass fraction, %).

Item	Yield	Grade			Distribution		
		Au */(g/t)	SiO_2	K_2O	Au	SiO_2	K_2O
Underflow	75.07	0.23	75.36	4.31	86.29	77.43	75.73
Overflow	24.93	0.11	66.13	4.16	13.71	22.57	24.27
Feeding	100.00	0.20	73.05	4.27	100.00	100.00	100.00

* Unit g/t.

3.3. Gold Recovery

The abundant minerals in the tailings samples were mainly sulfide ores, hematite, and limonite; hence, the recovery process of quartz was imperative to include the removal of impurities. The gold recovery, therefore, required the adoption of the high-intensity magnetic separation technique and then the flotation process. A grinding process was conducted before gold recovery to ensure the efficiency of subsequent quartz and feldspar recovery. The samples were ground into fine particles of no less than 85.6% of −0.074 mm. After high-intensity magnetic separation, another desliming procedure was performed to retrieve and purify quartz and feldspar. Figure 7 illustrates the technological process of gold recovery, and Table 6 summarizes the recovery results.

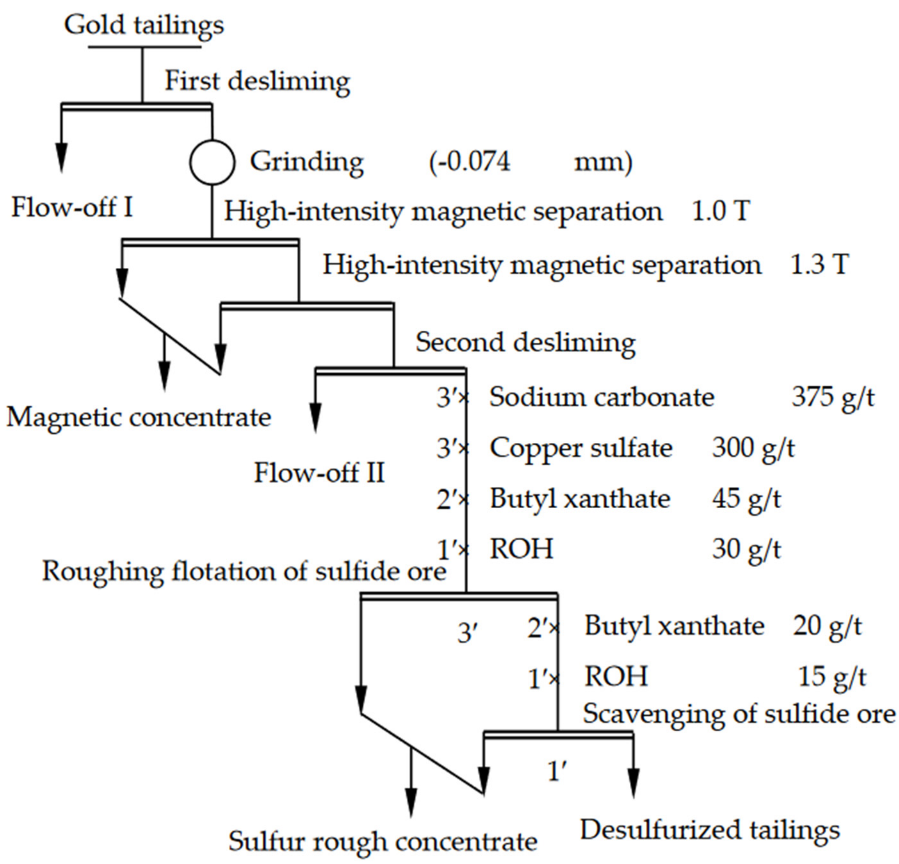

Figure 7. Technological process of gold recovery.

Table 6. Results of gold recovery (mass fraction, %).

Item	Yield	Grade			Recovery		
		Au */(g/t)	SiO_2	Fe_2O_3	Au	SiO_2	Fe_2O_3
Flow-off I	24.33	0.11	66.38	3.49	12.78	22.23	20.76
Flow-off II	26.19	0.13	67.27	2.88	16.27	24.25	18.44
Magnetic concentrate	14.96	0.41	67.07	14.17	29.30	13.81	51.84
Sulfur rough concentrate	1.71	3.18	61.23	11.43	25.98	1.44	4.78
Desulphurized tailings	32.81	0.10	84.71	0.52	15.67	38.27	4.18
Feeding	100.00	0.21	72.64	4.09	100.00	100.00	100.00

* Unit g/t.

Table 6 indicates that gold was enriched in the sulfur rough and magnetic concentrates, and the recovery of gold, which could be directly recycled by smelting for industrial purposes, reached 55.28% in both concentrates. SiO_2 was also enriched to a certain extent through this process (desulfurized tailings), and more than 95% of Fe_2O_3 was retrieved (desulfurized tailings), setting a good foundation for the subsequent recovery of quartz and feldspar.

3.4. Recovery of Quartz and Feldspar

3.4.1. Removal of Impurities

As mentioned above, desulfurized tailings improved the recovery potential of quartz and feldspar. The mineral composition and multi-element analyses of the desulfurized tailings are summarized in Tables 7 and 8, respectively. The quartz and K-feldspar contents in the desulfurized tailings after the desliming and gold recovery processes were more than 90%, and the main impurities were mica, carbonate minerals, and chlorite. Feldspar and quartz react harshly with Fe_2O_3, necessitating the extraction of the iron-containing minerals before the recovery of feldspar and quartz [35]. Consequently, the removal of impurities from the desulfurized tailings and the separation of the feldspar and quartz were the subsequent steps [36]. The main iron-containing minerals in the desulfurized tailings were hematite and limonite, which were removed by flotation. The flotation flowsheet for the removal of impurities is shown in Figure 8, and the flotation results are summarized in Table 9. After the removal of these impurities, the Fe_2O_3 content in the concentrate was 0.03%, indicating good potential for the subsequent recovery of quartz and feldspar.

Table 7. Main mineral composition of desulfurized tailings (mass fraction, %).

Minerals	Quartz	K-Feldspar	Plagioclase	Calcite	Chlorite	Sericite	Mica	Hematite, Limonite	Others
Content	59.6	30.5	7.3	0.8	0.3	0.8	0.2	0.3	0.2

Table 8. Chemical composition of desulfurized tailings (mass fraction, %).

Chemical Composition	Al_2O_3	SiO_2	Na_2O	K_2O	Fe_2O_3	MgO	CaO	S	Au * (g/t)
Content	6.77	84.71	1.33	3.46	0.52	0.61	1.76	0.03	0.10

* Unit g/t.

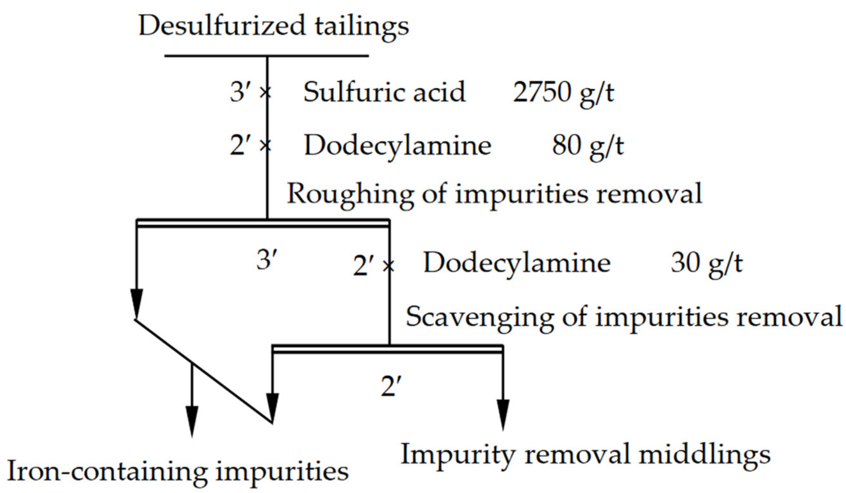

Figure 8. Flow sheet of impurity removal through flotation.

Table 9. Result of impurity removal (mass fraction, %).

Item	Yield		Grade of Fe_2O_3	Recovery Rate of Fe_2O_3	
	Feed *	Run-of-Mine **		Feed	Run-of-Mine
Iron-containing impurities	21.53	7.06	0.52	95.55	3.99
Impurity removal middlings	78.47	25.75	0.03	4.45	0.19
Feeding	100.00	32.81	0.53	100.00	4.18

*: "Feed" is the cleaning concentrate mass in relation to only the mass of this separation; **: "Run-of-mine" is the cleaning concentrate mass in relation to the run-of-mine mass. The following expressions are the same.

3.4.2. Recovery of Quartz and Feldspar through Flotation Separation

The flotation flowsheet for the recovery of feldspar [37] from the impurity removal middlings and the purification of quartz is shown in Figure 9, and the flotation results are summarized in Tables 10 and 11. The recovery of K-feldspar was up to 90% for the operation procedure and 18.36% for the run-of-mine. The K_2O content in the feldspar concentrate was 7.56%, which complies with China's ceramic industry standards. After recovering the

K-feldspar, further purification was performed to obtain quartz concentrate of commercial quality, although the SiO_2 content in the feldspar middlings was approximately 98.55%. The SiO_2 content in the K-feldspar concentrate increased to 99.8% under further purification, and quartz recovery was greater than 92.15% for the operation procedure and 19.50% for the run-of-mine.

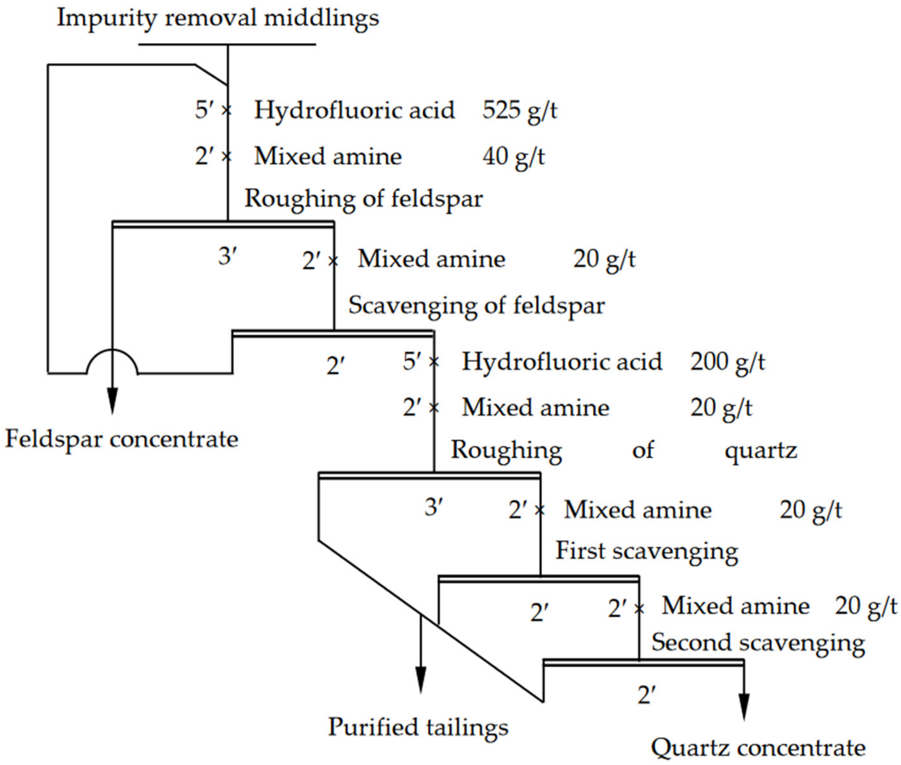

Figure 9. Flotation flowsheet for recovery of feldspar and purification of quartz.

Table 10. Results of feldspar recovery and quartz purification (mass fraction, %).

Item	Yield		Grade of K_2O	Recovery of K_2O	
	Feed	Run-of-Mine		Feed	Run-of-Mine
Feldspar concentrate	39.16	10.08	7.56	90.51	18.36
Feldspar middlings	60.84	15.67	0.51	9.49	1.93
Feeding	100.00	25.75	3.46	100.00	20.29

Table 11. Quartz purification results (mass fraction, %).

Item	Yield		Grade of SiO_2	Recovery of SiO_2	
	Feed	Run-of-Mine		Feed	Run-of-Mine
Quartz concentrate	90.93	14.25	99.87	92.15	19.50
Purified tailings	9.07	1.42	85.32	7.85	1.66
Feeding	100.00	15.67	98.55	100.00	21.16

3.5. Characteristics Analysis of Products

3.5.1. Analysis of Mineral Contents in Samples

Tables 12 and 13 present the chemical compositions of the coarse gold concentrate, quartz, feldspar, and sericite. The tables illustrate the qualities of the valuable minerals recovered from the gold tailings.

Table 12. Chemical compositions of coarse magnetic and sulfur concentrates (mass fraction, %).

Chemical Composition	Au */(g/t)	Na_2O	K_2O	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO
Magnetic concentrate	0.35	0.62	3.71	9.73	68.19	14.05	0.98	0.15
Sulfur rough concentrate	3.26	1.15	3.24	10.76	61.75	11.57	0.31	0.11

* Unit g/t.

Table 13. Chemical compositions of feldspar and quartz concentrates (mass fraction, %).

Chemical Composition	Na_2O	K_2O	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	TiO_2	Others
Feldspar concentrate	3.27	7.48	18.25	70.51	0.043	0.26	0.08	0.011	/
Quartz concentrate	0.01	0.02	0.03	99.87	0.014	0.01	0.01	0.01	0.019

Table 12 shows that gold was enriched in the magnetic and sulfur rough concentrates, signifying recovery qualities of 0.35 g/t and 3.26 g/t, respectively, which could adequately be consolidated for recycled gold. The chemical compositions presented in Table 13 indicate that the feldspar composition met China's national standards [38] specified for ceramics. The compositions presented in Table 13 also indicate that the quartz concentrate met China's standard for quartz used as raw material for industrial purposes to produce cover glass and liquid crystal glass substrates by adopting the overflow method.

3.5.2. Evaluation of Quartz Properties

The quartz produced by Sibelco, Belgium, is among the best in the world. Companies use only this quartz for manufacturing highly technical products that strictly require low iron content, high purity, specific colors, and other properties. The quartz produced by Sibelco and that from the gold tailings samples were compared. The temperature–viscosity curves of the glass products produced from both kinds of quartz were different. The results presented in Table 14 show that the high-temperature viscosity of the gold tailings quartz was lower than that of the Sibelco quartz, indicating that the gold tailings quartz easily melts and that it eliminates bubbles at high temperatures.

Table 14. Corresponding temperature–viscosity values for gold tailings and Sibelco quartz.

Intrinsic Viscosity (PaS)	Temperature (°C)		Fitted Calculation (°C)	
	Gold Tailings	Sibelco	Gold Tailings	Sibelco
10^2	1509.6	1535.2	1512.8	1536.4
$10^{2.5}$	1375.5	1402.2	1372.3	1402.8
10^3	1263.6	1289.8	1260.5	1289.5

Fitted formula: $\eta = -2.0 + 5050.7/(T - 250.2)$, where η is intrinsic viscosity and T is temperature.

The thermal expansion curves of glasses produced from both Sibelco and gold tailings quartz almost coincide; Figure 10a illustrates this phenomenon. The figure shows that the characteristics at working temperatures, such as softening, annealing, transition, and strain points, are almost the same for both products.

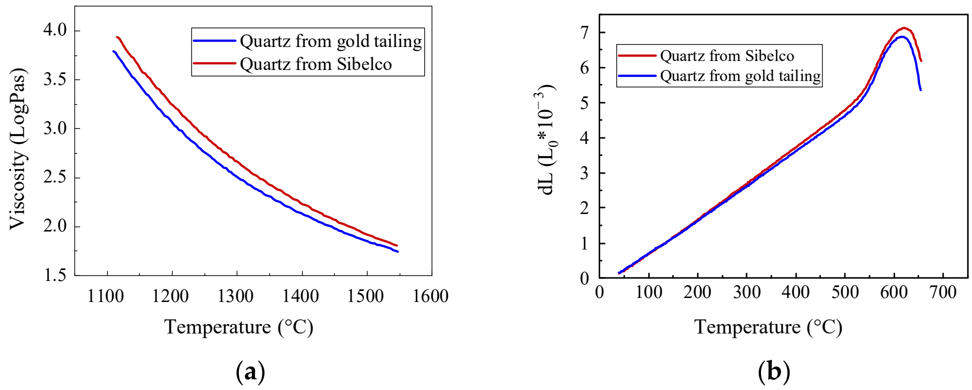

Figure 10. Quality comparison of quartz from Sibelco and from gold tailings. (**a**) Temperature–viscosity curve of Sibelco and gold tailings quartz. (**b**) Thermal expansion coefficient curve of Sibelco and gold tailings quartz.

Under the same composition and melting conditions, the optimal working temperature of a particular glass is closely related to the viscosity and thermal expansion coefficient of the glass, and this process determines the service performance of the glass. The viscometer thermal expansion coefficients of the Sibelco and gold tailings quartz were similar; these phenomena are illustrated in Figure 10b. Therefore, the properties of the fused glass products were also consistent. The gold tailings quartz concentrate met the industry standard for use as raw materials required to produce high-grade glass [39], such as cover glass for touch electronic products and TFT LCD liquid crystal substrate glass.

The comparative experiments of the Sibelco and gold tailings quartz indicate that the properties of the quartz recovered from the gold tailings are largely similar to those of the best (Sibelco) quartz. Therefore, the quartz recovered from the gold tailings samples were sufficient to produce high-technology instruments.

3.6. Economic Benefit and Environmental Impact Assessment

Gold tailings are a major solid waste produced during gold mining. However, they can also be used as an important secondary resource. A large quantity of non-recycled gold tailings is mainly disposed of in tailings dams, which constitutes a wastage of land resource and threatens environmental sustainability. This study of the recovery of gold, quartz, and other valuable components from gold tailings contributes to environmental protection and economic development by providing a way of reducing the amount of gold tailings disposed of in gold mining, extending the service life of tailings dams. Additionally, the study will help to reduce acidified wastewater in the disposal dam area, minimizing the risks of environmental pollution. Finally, the production of gold, quartz, K-feldspar, and other minerals is expected to yield economic benefits.

4. Conclusions

We systematically studied the properties of tailings samples from a quartz vein-hosted gold deposit. Certain valuable components (gold, feldspar, and quartz) of the gold tailings samples were obtained by selective desliming, flotation of gold bearing sulfide ore, removal of impurities containing iron, flotation separation of feldspar, and purification of quartz. The conclusions drawn are summarized as follows:

(1) The process mineralogy of the tailings samples obtained from the quartz vein-hosted gold deposits showed that the content of non-metallic minerals in the tailings was approximately 98%, comprising quartz, potassium feldspar, plagioclase, calcite, and sericite. Quartz, feldspar, and sericite, and that these were worth recovering because of their high concentration in the tailings. Moreover, the gold distribution in the tailings was 0.20 g/t, which also had a certain recovery value. The particle size distribution analysis indicated that the particles whose size fraction was +0.074 mm

achieved 37.68%, in which the distribution of gold and quartz reached 49% and 55%, respectively. The occurrence characteristics analysis showed that the quartz, K-feldspar, and sericite were partly metasomatized and associated.

(2) According to the process mineralogical properties of the tailings samples and the experimental results, an entire recovery process for valuable minerals in the tailings was established. Gold coarse ore, feldspar concentrates, and quartz concentrates were recycled following this process. A 1.74% yield of the sulfur rough concentrate was obtained, and this had a 3.24 g/t Au grade. The yield of the feldspar concentrates was 10.08%, and the K_2O content was up to 7.56%. Additionally, a 14.25% yield of the quartz concentrate and a 99.87% grade of SiO_2 were also achieved.

(3) By analyzing the comparative experimental results of the Sibelco and gold tailings quartz, we found that the high-temperature viscosity of the gold tailings quartz was slightly lower than that of the Sibelco quartz, and that the properties of molten glass products were largely the same for both quartz types.

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