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A comparison of dry and wet grinding on gold-bearing sulphide ore flotation

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Abstract: This study investigates the hypothesis that dry grinding prior to flotation can mitigate the adverse effects of galvanic interactions, improve the selectivity of gold flotation compared to wet grinding, and offer additional benefits due to water scarcity concerns and high water treatment costs. The effects of dry and wet grinding on the flotation behavior of gold-bearing sulphide ore were studied comparatively in terms of flotation test results and pulp chemistry parameters (pH, Eh, and dissolved oxygen). In addition, flotation tests without conditioning were also conducted following dry grinding in an attempt to minimize water contact further. Results demonstrated that dry grinding increased pulp potentials and dissolved oxygen levels, implying more oxidative conditions. Despite a lower mass pull with dry grinding, flotation recoveries and grades of gold and chalcopyrite were comparable to wet grinding, while dry grinding enhanced pyrite flotation at the rougher stage. Notably, flotation without conditioning effectively rejected pyrite and achieved higher grades for gold and chalcopyrite, indicating selective flotation. Therefore, dry grinding before flotation emerges as a viable alternative for gold and chalcopyrite flotation due to its improved selectivity while carefully optimizing flotation strategies and reagents to maximize recoveries.

Keywords: flotation, pulp chemistry, gold, conditioning, dry grinding

1. Introduction

Concentration of gold is carried out by gravity separation, cyanidation, and flotation methods, either directly or in complement to each other (Allan and Woodcock, 2001). Gold can occur in ores with a wide range of minerals: as native or free gold, as telluride minerals, as gold-carrying base metal sulphides, as gold-carrying iron sulphides, and as gold-carrying gangue minerals (Allan and Woodcock, 2001; Chryssoulis and McMullen, 2016). In terms of gold carrying sulphides, flotation is one of the most common beneficiation methods, applied successfully because of its selectivity, flexibility, and cost-efficiency (Klimpel, 1997; Teague et al., 1999a). While there are many studies reporting that naturally occurring native gold exhibits hydrophobic properties and can easily be floated, a significant proportion of gold is produced from sulphide ores (Aksoy and Yarar, 1989; O'Connor and Dunne, 1994; Klimpel, 1999; Dunne, 2005; Marsden and House, 2006; Oluklulu et al., 2019). Therefore, choosing the appropriate flotation scheme, such as bulk flotation of metals or selective flotation of gold, could strongly depend on the pulp chemistry that occurs due to the mineralogical composition of the ore (Bulatovic, 1997; Klimpel, 1997; Forrest et al., 2001).

The optimal liberation of minerals by grinding is crucial for enhancing flotation separation efficiency. Typically, sulphide mineral liberation is accomplished using wet processes, notably ball milling, prior to flotation (Bruckard et al., 2011). During this process, the interaction between the aqueous medium, minerals, and grinding media influences pulp chemistry parameters like pulp potential (Eh), pH, and dissolved oxygen (DO) (Chander, 2003; Huang and Grano, 2005; Fuerstenau et al., 2007; Bruckard et al., 2011). Steel grinding media, being more chemically active than sulphide minerals, undergoes oxidation, leading to the reduction of sulphide minerals (Javadi Nooshabadi et al., 2013). Consequently, this creates

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reducing conditions, hindering flotation by diminishing pulp potential and inhibiting collector adsorption onto mineral surfaces through the release of Fe^{+2} ions into the pulp, potentially resulting in the formation and redeposition of various species such as hydrophilic iron hydroxides ($Fe(OH)_2$, $Fe(OH)_3$) and iron oxy-hydroxides (FeOOH) on mineral surfaces (Senior and Trahar, 1991; Peng et al., 2003; Chandra and Gerson, 2009; Peng and Grano, 2010; Chelgani et al., 2019). As a result, galvanic interactions between the grinding media and sulphide minerals are one of the essential reasons that change the chemistry of the pulp, hence the flotation performance. Therefore, to avoid the negative effects of galvanic interactions that occur during wet grinding of sulphide minerals, dry grinding would be an option for future operations. Aside from this motive, environmental challenges, water scarcity, conservation of resources, and high costs of water treatment are critical concerns nowadays in mining and mineral processing (Chelgani et al., 2019; Tanhua et al., 2022). Nevertheless, there are limited studies on the flotation response of dry-ground sulphide minerals.

Feng and Aldrich (2000) compared the effects of wet and dry grinding on a sulphide ore flotation. This study showed that, following dry grinding, mineral surfaces are rendered more reactive by mechanical activation. Mechanical activation of the surfaces resulted in faster flotation kinetics while decreasing the flotation selectivity because of increased froth stability. In several studies, the effects of dry and wet grinding on flotation were investigated in the case of lead-zinc sulphide ores. Seke and Pistorius (2006) reported higher dissolved oxygen levels (DO) and positive pulp potentials (Eh) in flotation pulp following dry grinding, resulting in higher sphalerite grades and recoveries. Similar results were later reported by Palm et al. (2010), Koleini et al. (2012), Chapman et al. (2013), and Tokcan and Bozkurt (2021). In contrast to these results, Farrokhpay and Manouchehri (2012) found that sphalerite grades and recoveries were lower after dry grinding in a study investigating the effects of dry and wet grinding on flotation of complex Cu-Pb-Zn sulphide ore. They also found that wet grinding resulted in higher Cu recoveries than dry grinding due to the increased collector adsorption on mineral surfaces. Peltoniemi et al. (2020) compared the effects of both wet and dry grinding on the flotation of one Cu-Zn sulphide and one non-sulphide ores using a rod mill, suggesting energy efficiency was higher in wet grinding than dry grinding for both ores. In terms of flotation, while no significant difference was found for non-sulphide ore between grinding conditions, a loss in selectivity was observed in chalcopyrite with the sulphide ore. Similar findings regarding selectivity were also reported by Tanhua et al. (2022) in their study on the comparison of flotation performance of two different ores using a ball mill, including Cu-Zn and spodumene, in wet and dry grinding. They also reported significant activation of pyrite in the case of dry grinding for sulphide ore, which is attributed to the adsorption of atmospheric oxygen to the surfaces. Contrary to the aforementioned studies, Can and Başaran (2023) suggested that dry grinding resulted in an increase in Cu selectivity despite a decrease in Cu recoveries. Their findings are also in agreement with the positive pulp potentials observed following dry grinding compared to wet grinding (Seke and Pistorius, 2006). Liu et al. (2018) on the other hand, indicate that the effect of the grinding environment varies according to ore mineralogy in their study on different sulphide ores. According to their findings, for one ore, dry grinding provided better Cu flotation recoveries compared to wet grinding, on which lime addition was made to the mill, while no significant difference was observed between different grinding conditions for the other ore.

Various researchers have reached conflicting conclusions regarding the effects of dry and wet grinding on the flotation of various sulphide ores. In the case of gold ores, related studies are also limited. Gökçen et al. (2019) found that significantly higher gold recovery and grades can be obtained by collectorless flotation of a non-sulphide gold ore following dry grinding compared to wet grinding. In a study by Oluklulu (2020), the effects of the conditioning time were investigated in dry-ground sulphide gold ore. The study reported that the elimination of the conditioning time in dry ground ore flotation led to selective gold flotation by pyrite depression. To the best of the authors' knowledge, the effects of dry grinding and conditioning on the flotation of gold ore have not been studied before.

This research delved into examining the impacts of dry and wet grinding methods on the flotation characteristics of gold-bearing sulphide ore, with particular attention directed toward understanding the variations in pulp chemistry parameters, including pH, Eh, and dissolved oxygen (DO). Furthermore, flotation trials without conditioning were conducted following dry grinding to diminish mineral-water contact duration and mitigate galvanic interactions.

2. Materials and methods

2.1. Material

The ore sample utilized in this study originated from the vicinity of Artvin in Turkey's Northern Eastern Region. A pilot-scale Loesche VRM was used to dry-grind approximately 750 kg of ore into three different P_{80} sizes (156, 100, and 79 µm). Ground samples were sealed in nitrogen-purged 25-kg containers. The samples were then split into 1 kg portions and promptly placed in the freezer to avoid oxidation prior to their utilization in flotation test work. This work is part of a detailed flotation study conducted with the ore (Oluklulu, 2020). The P_{80} size of 156 µm samples was used to obtain the predetermined optimum flotation size of 100 µm to compare the effects of dry and wet grinding conditions on flotation.

Mineralogical analysis of the ore sample revealed that sulphide mineralization is dominated by pyrite (Py) and chalcopyrite (Cpy), the primary Cu-bearing mineral. The composite and binary particles of Cpy are primarily composed of Py and non-opaque gangue minerals. Non-liberated Cpy also occurs as interstitial grains at Py grain boundaries. Gold is predominantly present, mainly as free gold, with some association with Cpy and Py. Gold grains are mostly in the 30 µm and finer range. Quartz and mica are the most abundant minerals in the sample, with moderate amounts of feldspar, carbonates, clay, and magnesium silicates also present. A polished thin-section of the samples also shows that gold is mainly associated with Cpy and Py (Fig. 1).

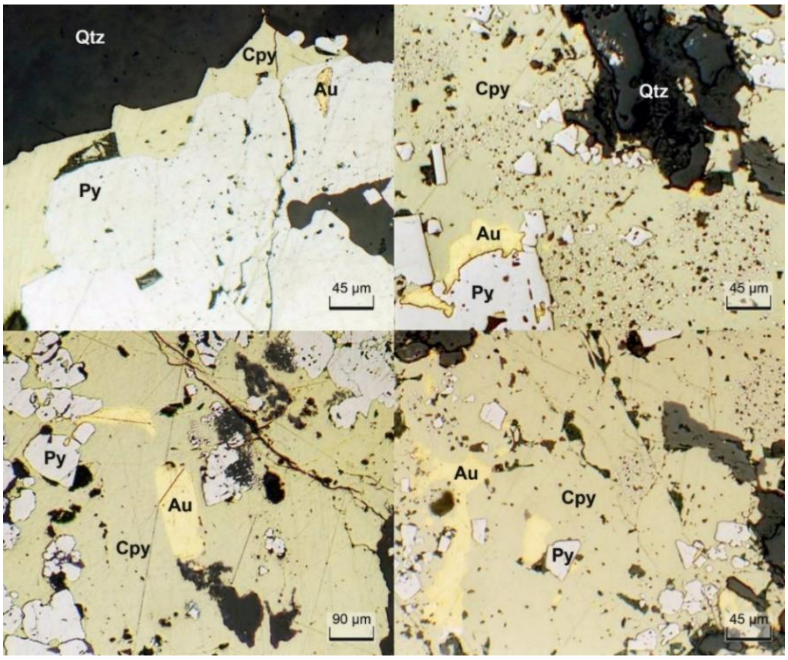

Fig. 1. The polished thin-section images of the ore

Chemical analyses of head samples and flotation products were carried out by Bureau Veritas Commodities Canada Ltd., Vancouver, BC, Canada, using ICP-ES/ICP-MS and by fire assay for gold. The results of the chemical analyses of the head assays are represented in Table 1. The ore contains 1.4 g/t Au and 0.2% Cu, as shown in the table. The iron (Fe) and sulphur (S) contents of the ore are 5.2% and 1.4%, respectively. According to mineralogical and chemical analysis, the ore can be defined as a low-sulphidation Au-Cu ore. The S content of the ore predominantly originated from Cpy and Py. Therefore, the Cpy and Py content of the ore are calculated to be around 0.6% and 2.3%, respectively.

Table 1. Head assays of the sample

Au (g/t)	Cu (%)	Fe (%)	S (%)	Cpy* (%)	Py* (%)
1.40	0.20	5.20	1.40	0.58	2.30

* Determined by the S balance

In **Błąd! Nie można odnaleźć źródła odwołania.**, size-by-size chemical analyses of the ore are shown. The analyses indicate that around 60% of the gold in the ore is finer than 38 µm, which aligns with the findings from mineralogical analyses. Generally, while the distribution of copper and iron across size fractions resembles that of gold, gold concentration is higher in the 38–25 µm range, whereas copper and iron are more prevalent in the 75–53 µm range compared to gold. It is important to note that approximately 20% of the gold is found in a size range close to the milling size. EDX analyses were also conducted on the flotation concentrates to further investigate gold liberation behavior. These analyses frequently identified free gold particles in the 10–50 µm range. Some of these results are illustrated in Fig. 2.

Table 2. Size-by-size chemical analyses of the sample (Oluklulu, 2020)

			Assay				Distribution			
Sieve (µm)	**Wt. (%)**	**Σ Passing (%)**	**Au (g/t)**	**Cu (%)**	**Fe (%)**	**S (%)**	**Au (%)**	**Cu (%)**	**Fe (%)**	**S (%)**
+212	1.17	100.00	0.32	0.03	1.96	0.74	0.27	0.18	0.44	0.55
-212+150	4.40	98.83	0.48	0.05	2.59	0.65	1.55	1.04	2.21	1.83
-150+106	10.92	94.43	0.69	0.08	3.42	0.92	5.57	4.48	7.25	6.43
-106+75	12.77	83.51	0.99	0.16	4.48	1.37	9.27	10.17	11.09	11.21
-75+53	11.63	70.75	0.95	0.25	5.46	2.02	8.17	14.71	12.31	15.05
-53+38	8.19	59.11	1.55	0.29	5.75	2.34	9.39	11.99	9.14	12.30
-38+25	6.49	50.92	2.61	0.26	6.14	2.45	12.47	8.62	7.73	10.19
-25	44.43	44.43	1.63	0.22	5.78	1.49	53.29	48.80	49.82	42.44
Σ	100.00		1.36	0.20	5.16	1.56	100.00	100.00	100.00	100.00

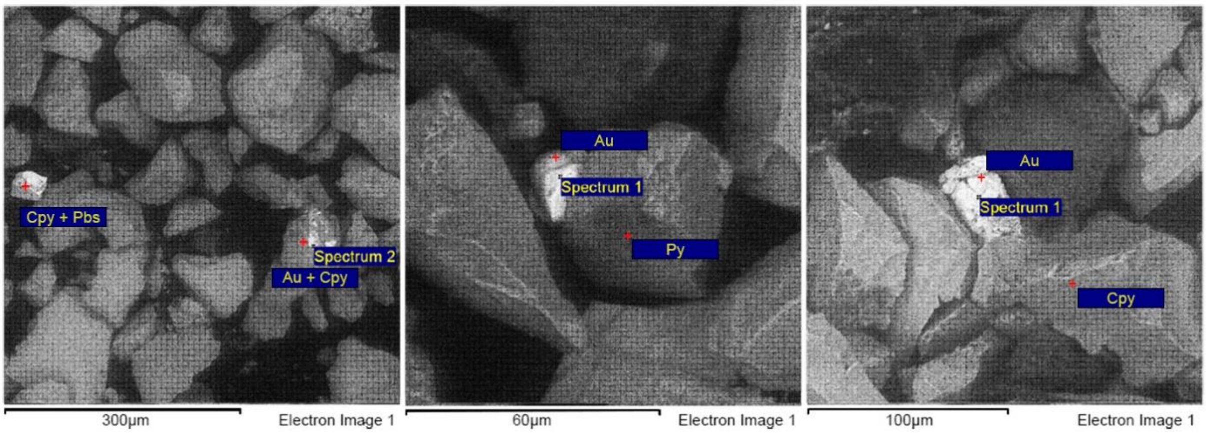

Fig. 2. EDX-SEM Images of the flotation concentrates (Oluklulu, 2020)

2.2. Methods

Samples were ground in a laboratory-scale rod mill with a diameter of 200 mm and a length of 250 mm, using stainless steel rods as grinding media. Wet grinding was conducted at 60 wt.% solids, while the same amount of solids was utilized in dry grinding to compare the effects of the grinding environment in gold flotation. Grinding times were predetermined to be 10 min to obtain a P_{80} size of 100 µm for both dry and wet grinding. Particle size distributions (PSD) were specified by using the Malvern Mastersizer Hydro 2000-MU instrument. Fig. 3 shows that the PSDs for both grinding conditions were quite similar to each other.

Batch flotation tests, including rougher and two cleaning stages, were carried out immediately after grinding for each charge at predetermined optimum conditions (Oluklulu, 2020). Tap water was used to prepare a 35% solid-by-weight pulp. Rougher and cleaner flotation tests were performed in 2.5 and 1.5 l flotation cells, respectively. The impeller speed was set at 1300 rpm, and the air flow rate was 7 l/min at the rougher stages. In the case of cleaning stages, impeller speed and air flow rate were adjusted to 1000 rpm and 5 l/min, respectively. The initial flotation pH of the ore was measured between 6.0 and

7.5 in relation to the grinding environment. For selectivity and Py depression, pH was adjusted to 10.0 at rougher flotation using lime, which was increased to 11.5 during cleaner stages. Potassium ethyl xanthate (PEX) and Aero 3894 were used as collectors, while AF70 was utilized as a frother. Flotation pH, pulp potential, and DO levels were measured during the conditioning of the flotation pulps by using Hach HQ40D portable meter equipped with pH, DO and platinum electrode. The pulp potential and DO values reported with respect to Ag/AgCl and mg/l, respectively. The changes in pulp chemistry resulting from dry and wet grinding conditions exhibit significant differences during the rougher flotation stage. However, these differences become negligible in the cleaning stages due to the increasing pH and extended contact time with water, which allow the reactions to reach equilibrium. Consequently, the effects of pulp chemistry on flotation outcomes have been evaluated solely based on the data from the rougher flotation stage. The flotation test scheme is illustrated in Fig. 4.

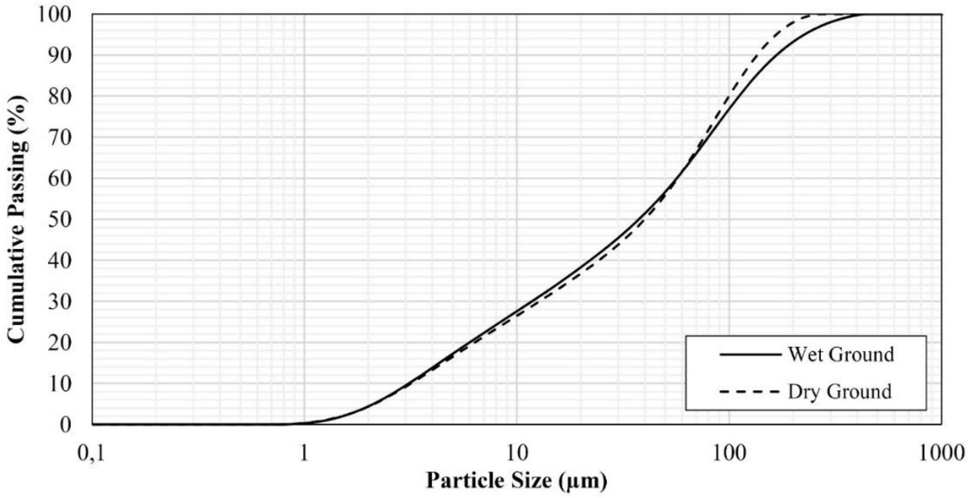

Fig. 3. Particle size distributions of the dry and wet ground samples

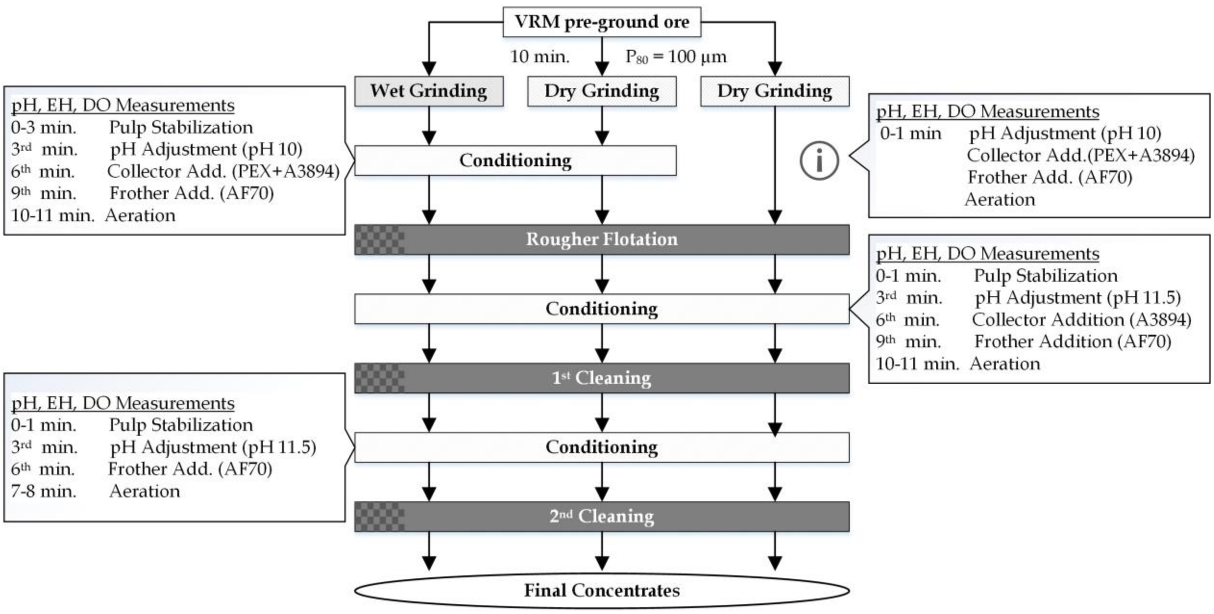

Fig. 4. Flotation test schemes for the studied conditions

An initial 3-minute conditioning was performed, with the aim of pulp stabilization before the reagents were introduced. Following the pH adjustment with lime, the pulp was conditioned for an additional 3 minutes to ensure pH stabilization. Collectors were then added at the 6th minute, and the pulp was conditioned for another 3 minutes. After a cumulative 9 minutes of conditioning, frother was introduced, and finally, the pulp was aerated for 1 minute before the flotation. In addition, a flotation test without conditioning (w/o conditioning) was also carried out following dry grinding in order to further shorten the water contact time, and hence possible galvanic interactions throughout flotation. During this test, lime, collectors, and frother were mixed in water before the sample was put in the flotation cell. The sample was then floated immediately.

The main distinction between the rougher and cleaner flotation stages was the addition of collectors at the cleaning stages. To avoid Au and Cpy depression, only A3894 was added in the 1st cleaning stage, and no collectors were added in the 2nd cleaning stage. The flotation times for the rougher, 1st cleaning, and 2nd cleaning stages were 300, 150, and 90 s, respectively. The froth was scraped at 30 s intervals. Flotation products were dried, weighed, and shipped for analysis. Flotation tests were performed with three repetitions, and the results were evaluated based upon average Au, Cpy, and Py recoveries and grades.

3. Results and discussion

3.1. Pulp chemistry

Measured Eh and pH values during rougher flotation tests in the case of dry and wet grinding are shown Fig. 5. The pulp pH difference was only observed after initial readings of the pulp following grinding. The pulp pH was around 7.5 after wet grinding, while it was about 6.3 after dry grinding. The pulp pH was then adjusted to 10.5 for flotation. As can be seen, positive Eh levels were observed at about +220 mV after dry grinding conditions, while Eh was in the negative region at about -220 mV after wet grinding. After the pH adjustment, Eh values approached each other to a certain extent and kept their levels until aeration, where the measurement was ended. The Eh value was still in the positive region at about 30 mV for the dry ground sample, while it was in the negative region at about -40 mV for the wet ground sample. As seen, in the case of dry grinding w/o conditioning, pH and Eh levels are similar to those of the dry grinding condition, indicating that the pulp chemistries of both conditions were the same at the beginning of flotation.

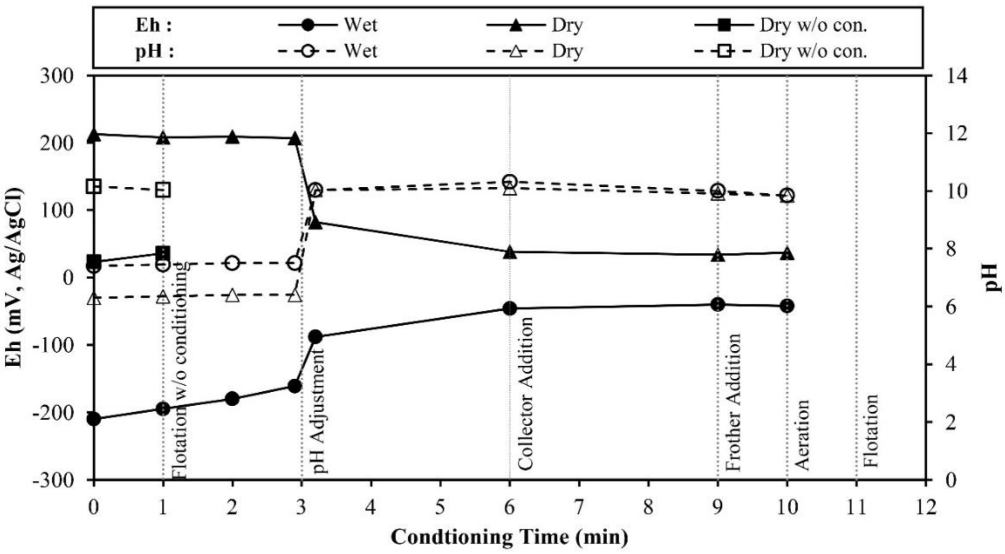

Fig. 5. Change in Eh and pH values of flotation pulps during rougher flotation tests

Measured dissolved oxygen (DO) levels during rougher flotation for different grinding environments are shown in Fig. 6. As seen, DO saturation was significantly high at about 8.2 mg/l during the conditioning of the dry ground samples. A slight decrease was observed after the pH adjustment, but in general, DO levels were stable at about 7.8 mg/l during the pulp conditioning. The same trend followed in the case of dry grinding w/o conditioning. As for the wet ground sample, DO levels were almost equal to zero at the beginning of the conditioning. After the pH adjustment, an increase in DO was observed during the conditioning of the pulp. Before the beginning of the froth scraping, the measured DO saturation of the pulp was 3.1 mg/l, which was considerably lower than the dry ground sample. In general, dry grinding resulted in more oxidative conditions compared to wet grinding.

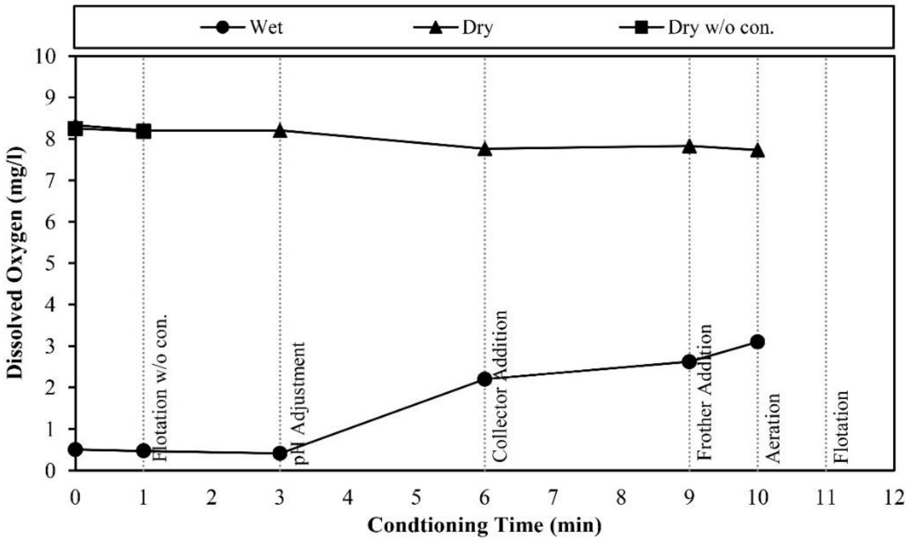

Fig. 6. Change in dissolved oxygen values of flotation pulp during rougher flotation tests

Several researchers have also reported positive pulp potential and higher DO levels (Seke and Pistorius, 2006; Koleini et al., 2012; Can and Başaran, 2023). The higher pulp potentials and dissolved oxygen measured after dry grinding indicate the absence of oxygen consumers, such as metallic iron and unstable sulphide species, in the dry ground ore compared to wet grinding. It is well-established that galvanic interactions between minerals and media occur during the wet grinding of sulphides, resulting in alterations across several factors throughout the flotation (Teague et al., 1999b; Huang and Grano, 2005). Notably, as the dissolved oxygen content decreases, the corrosive wear of the grinding media intensifies, thereby elevating the concentration of Fe ions within the pulp (Grano and Huang, 2006). Concerning mineral surfaces, it has been proposed that wet grinding of sulfides primarily involves chemical surface reactions of the resultant products. In contrast, dry grinding predominantly influences the oxidation of mineral surfaces (Feng and Aldrich, 2000). Moreover, surface analyses have revealed that dry ground samples exhibit more oxygen components on their surfaces than wet ground samples (Chapman et al., 2013). In other words, the pulp following dry grinding has higher Eh and DO than wet grinding. This higher DO level in the pulp can cause a higher H_2O_2 (strong oxidizing agent) concentration on the surface of dry ground samples than the wet ground ones (Javadi Nooshabadi et al., 2013). The presence of elevated oxygen species on mineral surfaces may diminish or enhance their floatability, contingent upon the nature of the minerals (Chelgani et al., 2019).

3.2. Flotation test results

Flotation results for Au are shown in Fig. 7. Overall, dry and wet grinding conditions had negligible effects on the flotation performance of Au. In the rougher flotation, a concentrate with 7.5 g/t Au and 75.3% recovery was obtained following wet grinding, whereas dry grinding resulted in 10.9 g/t Au and 73.4% recovery. Throughout the cleaning stages, the recoveries declined while grades increased, as anticipated. Final concentrates having 50.1 g/t Au with a recovery of %63.6 and 71.1 g/t Au with a recovery of %59.4 were obtained for wet and dry grinding, respectively. As for dry grinding w/o conditioning, despite a roughly 5% loss in recovery in the rougher flotation, the Au grade more than doubled to 21.7 g/t. Although the recovery at the 2nd cleaning stage was significantly lower (48.1%) compared to other conditions, Au selectivity was maintained with a superior grade of 91.9 g/t.

Flotation results for Cpy are presented in Fig. 8. In general, although the effect of dry and wet grinding on Cpy recoveries is marginal, higher Cpy grades were obtained with dry grinding compared to wet grinding. While concentrates with approximately 58% Cpy recovery were obtained under both conditions, a slightly higher Cpy grade was obtained at 3.2%, compared to the 2.4% of the wet grinding. As for dry grinding w/o conditioning, a marginally lower recovery was obtained at 51.3%, with a remarkably higher grade of 6.9%. Throughout the cleaning stages, recoveries decreased, with similar tendencies in all conditions, as the grades increased. After 2nd cleaning stages, quite similar Cpy recoveries were obtained for wet and dry grinding, at 48.4% and 46.7%, respectively, while the Cpy grade achieved after dry grinding was significantly higher at 21.2%, compared to 16.2% for wet grinding. After two cleaning stages, dry grinding w/o conditioning resulted in an exceptional 33.7% Cpy grade with a relatively low recovery of 40.6%.

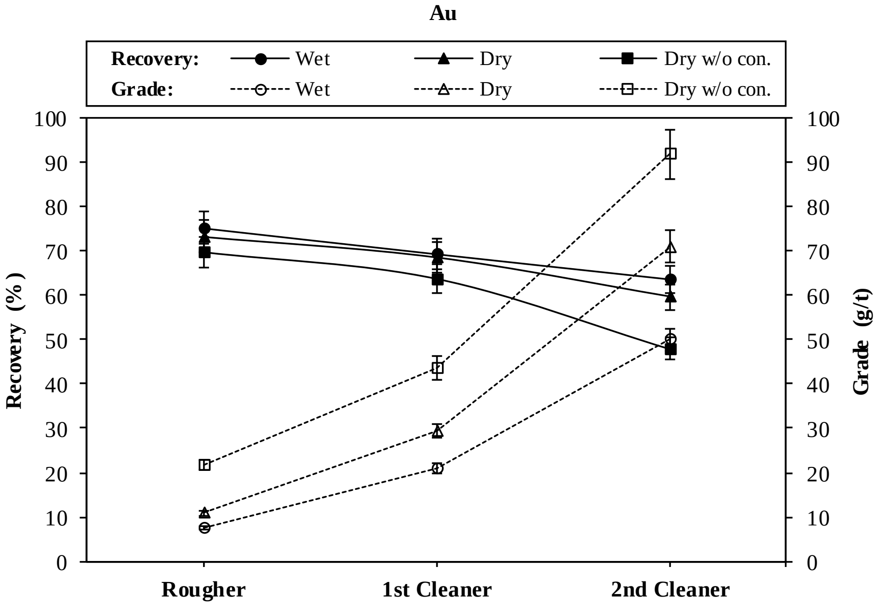

Fig. 7. Au recoveries and grades in the flotation stages

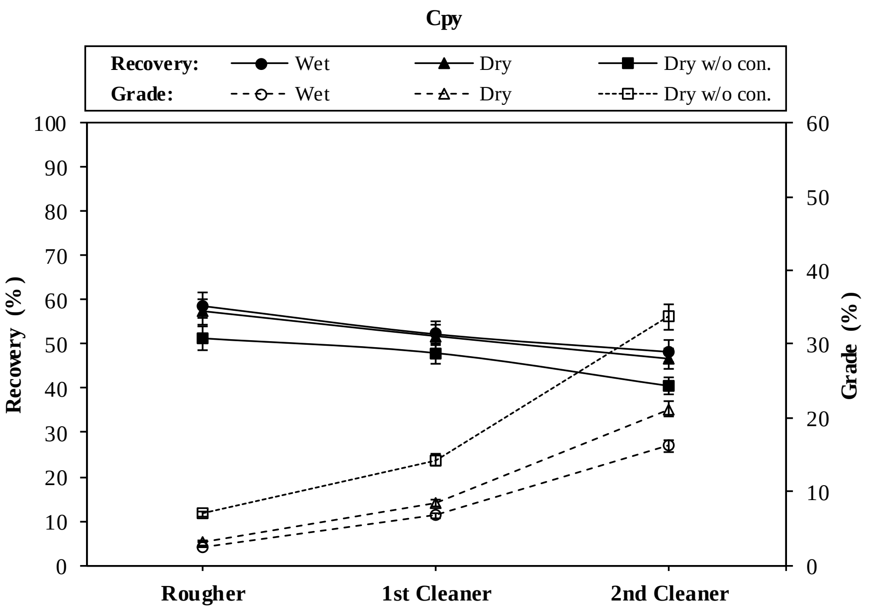

Fig. 8. Cpy recoveries and grades in the flotation stages

Flotation results for Py are presented in Fig. 9. Considering the results for Py, wet grinding resulted in a concentrate recovery of 72.1% and an 11.6% Py grade. Dry grinding, derived from Au and Cpy, enhanced Py flotation to a certain extent, as indicated by the increasing grade (15.7%) and recovery (77.7%). However, eliminating the conditioning time reversed the Py-promoting effect of dry grinding, resulting in a concentrate with a 36.7% Py grade and 66.3% recovery. While Py recoveries decreased in a similar trend across all conditions in the 1st cleaning stage, Py grades increased at a higher rate in dry grinding conditions compared to wet grinding. Nevertheless, in the final concentrates obtained after 2nd cleaning, the Py grades reached approximately 38% for all conditions. Moreover, the Py recovery obtained in the dry grinding condition drastically decreased to 22.6%, which is lower than the 30.7% obtained by wet grinding. The lowest Py recovery was obtained following dry grinding w/o conditioning at 11.2%. As a result, the Py-promoting effect of dry grinding disappeared at the second cleaning stage, and with no doubt the best Py rejection was achieved following dry grinding w/o conditioning.

Fig. 10 shows the mass pull values for the studied conditions during the flotation stages. As the figure shows, the concentrates' mass pulls significantly varied between conditions. The highest mass pull value was obtained following wet grinding in rougher flotation at 13.8%. After dry grinding, the mass pull value dropped significantly, and with the elimination of the conditioning, it decreased further, from 10.2% to 4.3%. They also decreased as expected in the 1st cleaning stage, following the same order. Although the differences seem to decrease in the 2nd cleaning stages, the highest mass pull was obtained with wet grinding at 1.7%, while the mass pull value of the dry grinding w/o conditioning was less than half that of wet grinding at 0.7%.

Py

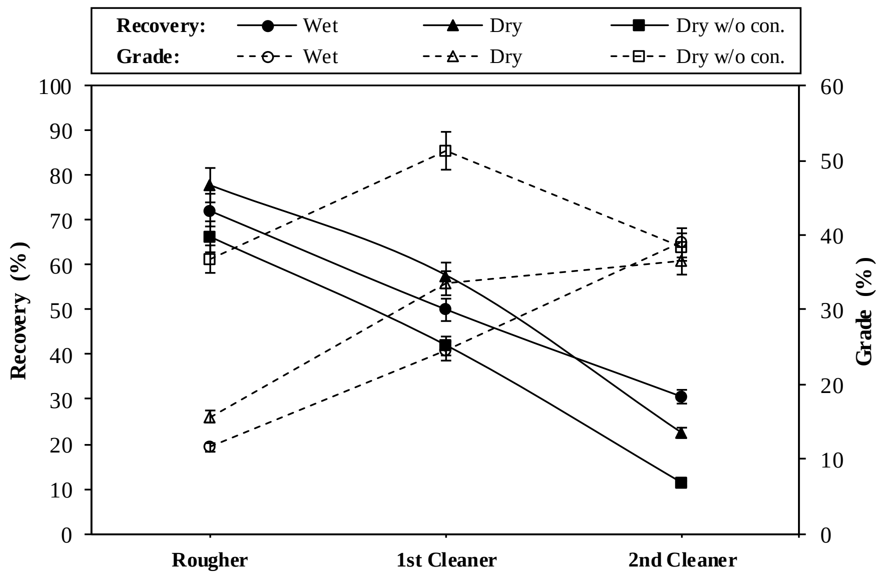

Fig. 9. Py recoveries and grades in the flotation stages

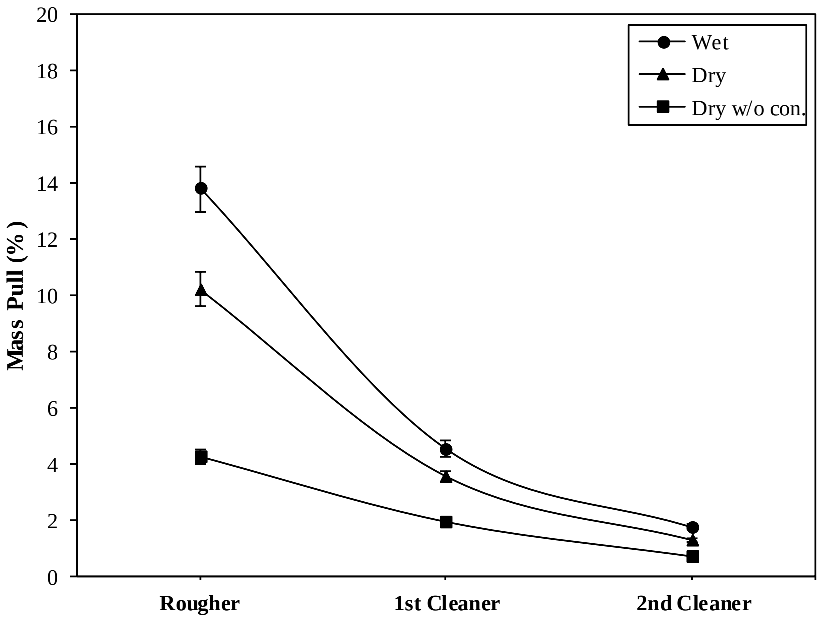

Fig. 10. The mass pull values in the flotation stages

The metallurgical balances of the studied conditions are also summarized Table 3 in as the averages of the flotation tests performed.

Table 3. The metallurgical balances of the studied conditions

Condition	Product		Mass Pull (%)	Grades			Recoveries		
				Au (g/t)	Cpy (%)	Py (%)	Au (%)	Cpy (%)	Py (%)
Wet Grinding	Rougher	C*	13.78	7.47	2.47	11.57	75.27	58.61	72.09
		T**	86.22	0.39	0.28	0.72	24.73	41.39	27.91
	1st Cleaner	C	4.52	20.97	6.73	24.52	69.32	52.29	50.11
		T	9.26	0.88	0.40	5.25	5.95	6.32	21.98
	2nd Cleaner	C	1.73	50.08	16.21	39.05	63.55	48.32	30.63
		T	2.78	2.83	0.83	15.48	5.78	3.96	19.49
	Cal. Head		100.00	1.37	0.58	2.21			
Dry Grinding	Rougher	C	10.19	10.89	3.24	15.69	73.38	57.26	77.73
		T	89.81	0.45	0.27	0.51	26.62	42.74	22.27
	1st Cleaner	C	3.54	29.32	8.41	33.53	68.64	51.67	57.68
		T	6.65	1.08	0.48	6.20	4.74	5.59	20.05
	2nd Cleaner	C	1.27	71.07	21.17	36.59	59.65	46.62	22.57
		T	2.27	5.99	1.28	31.81	8.99	5.05	35.11
	Cal. Head		100.00	1.51	0.58	2.06			
Dry Grinding W/O Conditoning	Rougher	C	4.26	21.70	6.94	36.76	69.69	51.23	66.23
		T	95.74	0.42	0.29	0.83	30.31	48.77	33.77
	1st Cleaner	C	1.93	43.76	14.30	51.40	63.73	47.91	41.99
		T	2.33	3.39	0.82	24.61	5.96	3.32	24.23
	2nd Cleaner	C	0.69	91.90	33.72	38.43	48.04	40.55	11.27
		T	1.24	16.80	3.43	58.66	15.69	7.36	30.72
	Cal. Head		100.00	1.33	0.58	2.37			

C* : Concentrate, T** : Tailings

In general, despite varying Ehs and DO levels, there is no difference in the flotation behavior of Au and Cpy in terms of dry and wet grinding conditions at the rougher stages. In contrast to these findings, Lepetic (1974) and Koleini et al. (2012) reported enhanced Cpy flotation following dry grinding. Furthermore, lower mass pulls obtained following dry grinding than wet grinding can be attributed to the instability of the froth structure, as also noted by Can and Başaran (2023). On the other hand, the increased pyrite recovery and grades resulting from dry grinding are attributed to the high pulp potential and oxygen levels in the environment created by dry grinding, which promotes pyrite flotation. Similar results were also observed by Tanhua et al. (2022) after dry grinding. Even though the pulp chemistry difference was negligible at the first cleaning stages, Au, Cpy, and Py recoveries and grades followed similar trends as in the rougher stages despite the increasing pH. This indicates inefficient Py depression, possibly due to the further collector addition to avoid Au and Cpy loss. In the 2nd cleaning stage, where no collector is added, the same trend continues for Au and Cpy. At the same time, a remarkable decrease in Py recovery with a similar grade indicates that more effective Py depression was achieved following dry grinding. This might be due to the fact that, in the case of collectorless flotation of gold ores, oxidative conditions produced by dry grinding offer more favorable conditions for effective Py rejection (Oluklulu et al., 2019; Oluklulu, 2020).

In flotation tests w/o conditioning following dry grinding, no change in pulp chemistry (Eh and DO) was observed. The remarkably decreased Py recovery shows that dry grinding w/o conditioning significantly inhibited Py flotation while having a limited decrease in Au and Cpy recoveries. Au, Cpy, and Py grades increased noticeably with the significant drop in the mass pull, indicating that flotation w/o conditioning resulted in selective bulk flotation of Au, Cpy, and Py from the non-sulphide gangue. These results could be attributed to the limited collector-mineral interactions and reduced entrainment. In a way, flotation tests w/o conditioning imitated collectorless flotation to a certain extent; hence, better selectivity and Py rejection were acquired compared to both dry and wet grinding. The trends observed in recoveries and grades of Au, Cpy, and Py during the rougher stage were maintained during the 1st cleaning stage, at which the collector was utilized. In the 2nd cleaning stage, where no collector is added, no significant change was observed for Cpy flotation behavior. On the other hand, the apparent decrease in Py recovery and grade shows that the best Py rejection has been achieved after dry grinding w/o conditioning. It's also important to keep in mind that, according to the ore's mineralogical characteristics, Au-associated Py may be the cause of the loss in Au recovery. Furthermore, the best Au and Cpy grades were also obtained at this condition, indicating selective Au and Cpy flotation. The elimination of the conditioning time can counteract the Py-promoting effects of dry grinding by reducing the collector-mineral interactions that take place during the conditioning of the flotation pulp. In other words, it has been revealed that the collector-mineral interaction plays a greater role in Py depression than the galvanic interactions that are expected to be minimized by dry grinding. Also, it's understood that this approach provides an effective Py depression as well as a more selective Au and Cpy concentrate from gangue minerals.

4. Conclusions

Different grinding environments had significant effects on the pulp chemistry and the flotation response of the gold-bearing sulphide ore, evaluated as Au, Cpy, and Py grades and recoveries. Main findings and possible implications are summarized below:

- Dry grinding resulted in higher pulp potentials (Ag/AgCl) and DO levels than wet grinding, indicating higher oxidative conditions and, reduced galvanic interactions. Despite decreasing mass pulls, increasing Py recoveries implicating that dry grinding provided more favorable pulp chemistry for Py flotation without noticeably altering Au and Cpy flotation. Nevertheless, enhanced Py flotation was diminished at subsequent cleaning stages where no collector was utilized, which can be attributed to Py's higher collector affinity compared to Au and Cpy.
- Dry grinding w/o conditioning inhibited Py flotation remarkably at the rougher flotation stage, suggesting that the mineral and collector interactions play a greater role in Py flotation than the pulp chemistry. On the other hand, Au and Cpy losses were minimal, possibly due to the collectorless flotation characteristics of these minerals. Flotation after dry grinding w/o conditioning provide increased selectivity for Au and Cpy as indicated by significantly increased Au and Cpy grades and decreased mass pulls and Py recovery.
- Dry grinding preceding flotation could present a viable alternative for Au and Cpy flotation owing to its enhanced selectivity. Nevertheless, carefully optimizing flotation strategies and reagents is imperative to maximize recoveries, given the marked disparities in pulp chemistry between dry and

wet grinding. Moreover, a thorough assessment of the practical feasibility of implementing dry grinding processes at a plant scale is paramount.

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