

# Comparative Study of Hydrometallurgical (Aqua Regia) and Pyrometallurgical (Direct Melting) Method for Gold Recovery from Gold Jewellery Polishing Dust

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**Abstract.** Polishing in jewellery manufacturing produced polishing dust containing gold particle that need to be recovered. Two methods are available, hydrometallurgical method (aqua regia) and pyrometallurgical method (direct melting). The two methods are compared from recovery, process time, economic, and safety aspects. Recovery of direct melting show higher result of 99.97 compared to 97.08% recovery of aqua regia from fire assay sample. Direct melting is shorter in process time compared to aqua regia due to simpler steps involved, thus reducing production time, minimizing labour requirement, and human error. Inert slag waste produced by direct melting also safer and cheaper for handling compared to acidic waste produced by aqua regia. From safety aspect, direct melting with appropriate Air Pollution Control System (APCS) has manageable thermal risk compared to toxic gas and corrosive risk of aqua regia. From these aspects, jewellery industry can be recommended to transition to direct melting compared to aqua regia method for gold recovery from polishing dust.

## 1 Introduction

Polishing is a process in jewellery manufacturing to produce a mirror surface. This process is performed mechanically using polishing compounds and smooth surfaces such as polishing wool wheels for jewellery surfaces and felt bob wool for hard-to-reach crevices. Polishing compounds/rouges are mixtures of oxide particles (CaO, Cu<sub>2</sub>O, iron oxide, SiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub>) and binding agents based on wax or grease [1]. Polishing dust needs to be recovered in the jewellery industry to reduce net gold loss during production and implement closed-loop production.

The current gold recovery process involves roasting scrap material and extraction using hydrometallurgical methods with dissolution in aqua regia. This process has many stages that slow down production time, such as neutralization, denoxing, precipitation, and smelting. Strict safety and environmental procedures are also required due to the risk of toxic gases and corrosive acids. Recovery using aqua regia produces large volumes of liquid waste and requires special handling (neutralization) before disposal, increasing costs [2].

An alternative method is a pyrometallurgical method similar to the pyrometallurgical extraction method used in small-scale/artisanal mining in the Philippines and Tanzania, namely smelting with borax. An experiment conducted by Peter Wu et al. [3] in Kalingga, Northern Philippines, found that this method successfully extracted three times more gold from gold concentrate than the amalgamation method. During smelting, borax

acts as a flux to form slag with oxide materials, and due to its lower density, it separates from the gold metal, which settles at the bottom of the crucible. The same principle can be applied to industrial jewellery polishing dust, which also contains oxide particles.

This paper compares hydrometallurgical and pyrometallurgical methods for recovering gold from polishing dust generated in the jewellery industry. Regarding the recovery rate, process time, and economic aspects, we use actual data from companies (operational trials). On the other hand, for sustainability and safety aspects (residue, gas emissions, and mitigation), we base our arguments on scientific literature. This paper aims to provide comprehensive comparisons are based on a combination of field data and literature reviews that can serve as a basis for consideration in the jewellery industry.

## 2 Process Description

### 2.1 Pre-Treatment

Polishing dust material can be defined as fine powder derived from the process of polishing gold jewellery. This material contains fine gold alloy particles, polishing compounds, and inorganic contaminants. Before characterization and recovery process, the polishing dust must first undergo preparation, which includes:

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1. Initial weighing: The polishing dust scrap was weighed and recorded
2. Burning: The material was burned in an oven at 800 °C for 3 hours to remove organic contaminants
3. Grinding: After burning was completed and the material had cooled, it was grounded using a ball mill to uniformly reduce particle size
4. Sieving: This process was carried out using a 200-mesh sieve to filter the material, resulting in a fine powder to accelerate the rate of chemical reactions and removing coarse metal impurities such as iron fragments.
5. Mixing: All the fine material was mixed using a mixer to ensure the material was homogeneous, ensuring accuracy in fire assay sampling.

After all material preparation steps were completed, to estimate the gold content in the material, sampling and testing were conducted. Two samples (primary and duplicate), each weighing 5 grams, were taken for gold content testing using the Fire Assay method.

## 2.2 Gold Analysis Standards (Fire Assay)

Fire assay is a gravimetric process for determining gold content, consisting of crucible fusion, cupellation and parting stages. Firstly, in crucible fusion stage, the dust was mixed with flux and litharge to separate the oxide components in the slag and the metallic components (gold and base metals) in the lead button. Next, in the cupellation stage, the base metals and lead were oxidized to form a mixture of oxides that were absorbed by the cupel during the cupellation process, which leaved alloy of gold and silver. Lastly, the silver is separated from the gold using nitric acid solution (parting) to obtain the final weight of the gold. The gold content in the sample is determined based on the following equation:

$$F = \frac{m_1}{m_2} \quad (1)$$

$$W = \frac{m_4 \times \bar{F}}{m_3} \times 1000 \quad (2)$$

Correction factor was first calculated using high purity gold as a calibration for gold loss to slag and cupel in the process,  $m_1$  is the initial control mass, and  $m_2$  is the final control mass. For high gold content alloy (>99%) the correction factor must be less than 0.016%.  $W$  is the gold content in parts per thousand,  $\bar{F}$  is the correction factor,  $m_3$  is the mass of the sample before parting, and  $m_4$  is the mass of the sample after parting [4]. All masses ( $m_1, m_2, m_3, m_4$ ) are expressed in grams (g). Correction factor ( $F$ ) is the ratio of initial and final masses in the control. The value of  $W$  is expressed in parts per thousand.

Recovery of the aqua regia method and direct melting method will be calculated using the following equation:

$$\%Rec = \frac{\% \text{ gold content of metal} \times \text{mass of metal}}{W \times \text{mass of processed polishing dust}} \times 100\% \quad (3)$$

Metal retrieved after the processed was fire assayed to determine the % gold content. Recovery can be calculated by dividing the mass of the metal retrieved (g) multiplied by the %gold content divided by the gold content (W) in the polishing dust multiplied by the amount of polishing dust processed (g) with aqua regia method or direct melting method.

## 2.3 Hydrometallurgical Process (Aqua Regia Method)

The stages of the gold recovery process from polishing dust using aqua regia are as follows:

1. Leaching: The sample was placed in a reaction vessel, and aqua regia (a mixture of 1:3 concentrated  $HNO_3$  and  $HCl$ ) was added at a material-to-acid ratio of 1:4 (1 kg of dust with 4 liters of aqua regia).
2. Second Leaching: After the initial reaction, the solution was filtered. The solid residue was then reacted again in the second leaching stage with fresh aqua regia to ensure maximum gold dissolution.
3. Denoxing (Urea Addition): Urea was slowly added to the solution to neutralize any remaining nitric acid ( $HNO_3$ ) in the aqua regia solution after the gold dissolution process was completed.
4. Precipitation (Addition of SMB): After all residual nitric acid has been neutralized, Sodium Metabisulfite (SMB) was added to the solution to precipitate the gold by reduction reaction.
5. Melting: The precipitate was then filtered, dried, and melted in a crucible to produce metallic gold.

## 2.4 Pyrometallurgical Process (Direct Melting Method)

This method involves mixing prepared dust with a combination of flux and melting the mixture directly. The composition of the charge is as follows:

**Table 1.** Direct melting charge composition

Items	Qty (kg)
Burned Dust	3
Borax Decahydrate	3
Sodium Nitrate	1,5
Sodium Carbonate	0,75
Copper	0,3

The steps of the process are:

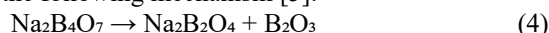
1. Mixing: The sample was mixed with a amount of flux (decahydrate borax, sodium nitrate, sodium carbonate) and copper which acted as collector metal based on the composition in Table 1.
2. Melting: The mixture was placed in a crucible and heated in an electric furnace to a temperature of 1100 °C for 2 hours.
3. Pouring and Separation: The molten mixture was poured into a cone-shaped mold. The denser gold-copper alloy would settle at the bottom, while the

lighter slag would float on top. After cooling, the metal at the bottom was retrieved.

The chemical mechanism of each component in direct melting is as follows:

- Sodium nitrate ( $\text{NaNO}_3$ ) is an oxidizer. Sodium nitrate can decompose, releasing oxygen into the melt and oxidizing metallic impurities in the melt (zinc from the alloy) into oxides. These oxides then dissolve in the borax flux and become part of the slag.

- Borax (sodium tetraborate,  $\text{Na}_2\text{B}_4\text{O}_7$ ) functions as a flux. Borax decomposes into sodium metaborate ( $\text{Na}_2\text{B}_2\text{O}_4$ ) and boric anhydride ( $\text{B}_2\text{O}_3$ ) according to the following mechanism [5]:



Boron trioxide can dissolve basic metal oxides (such as  $\text{Fe}_2\text{O}_3$  and  $\text{ZnO}$ , which originate from oxidation with sodium nitrate). This reaction reduces the viscosity of the slag, making it more fluid and facilitating the heavier gold particles to sink and accumulate at the bottom.

- Sodium carbonate (soda ash,  $\text{Na}_2\text{CO}_3$ ) is a strong basic flux (network modifier). Sodium carbonate reacts with  $\text{SiO}_2$  (network former), one of the components of the compound poles. This reaction forms sodium silicate ( $\text{Na}_2\text{SiO}_3$ ), a compound with a relatively low melting point [6].



- Copper (Cu): Functions as a collector metal for gold contained in the smelting of polishing dust. Based on the Au-Cu phase diagram, gold has high solubility in copper at temperature higher than 410 °C which formed solid solution phase AuCu, thus during smelting, gold particles will dissolve more easily in molten copper rather than being trapped in the slag. This process will produce a homogeneous liquid metal phase that will settle at the bottom of the crucible, resulting in maximum gold recovery.

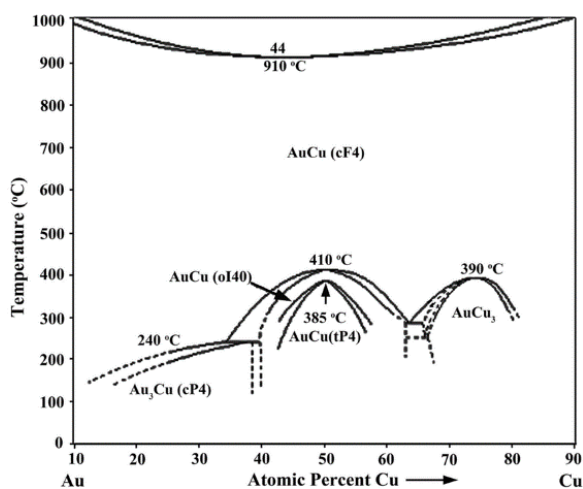


Fig. 1. Au-Cu phase diagram [7]

### 3 Result and Discussion

#### 3.1 Metallurgical Perspective

From a metallurgical perspective, both methods (aqua regia and direct melting) produced high recovery. Based on research conducted by Reddy and Mishra (1999) polishing dust that has been roasted at 700 °C will resulting in 99.5% gold recovery using aqua regia [1]. However, from trial conducted it is found that aqua regia method resulted in the recovery of 97.08%. On the other hand, the direct melting method shows lower performance from paper review. Experiment conducted by Angeloci-Santos (2013) [8] for direct melting process with melting temperature of 1063 °C with flux and concentrate ratio of 1:1:1:0.25:0.25 (Conc: Borax:KNO<sub>3</sub>:SiO<sub>2</sub>:NaHO<sub>3</sub>) found that 15.3% of gold is trapped in slag phase. Maganga et al (2024) [11] conducted direct melting experiment with added litharge (PbO) and flour in the flux mixture similar to fire assay process to act as collector metal, 1250 °C melting temperature, and 90 minutes melting time, resulting in 87% recovery. The drawback from adding litharge is Pb contamination in the final product and health risk with lead melting. Method employed in this paper mitigate the problem from previous research by replacing litharge with copper as collector metal and increasing the melting time to 2 hours to help with slag-metal phase separation. This replacement yielded higher recovery of 99.97% from trial conducted.

From the results of operational trials conducted on an industrial scale at our company, both the aqua regia and direct melting methods showed high metallurgical performance, but with significant differences in recovery rates. The hydrometallurgical method using aqua regia produced a recovery of 97.08% of the gold value determined by fire assay. Meanwhile, the pyrometallurgical method through direct melting showed higher performance with a recovery of 99.97% by fire assay.

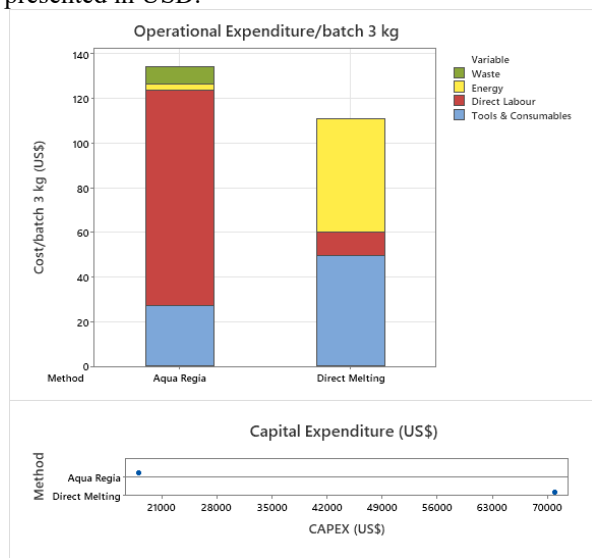
This difference indicates that, although aqua regia is theoretically capable of dissolving gold almost completely, in operational practice there are gold losses that cannot be completely avoided, especially during the filtration, precipitation, and residue handling stages. In contrast, direct melting allows gold to be concentrated directly into the collector metal phase, thereby minimizing losses during the process and producing a recovery that is closer to the fire assay analysis value.

Apart from the ability to recover gold, another aspect that is no less important is the efficiency of the process time. When working with the same batch quantity, the pyrometallurgical method clearly provides a faster process because it has simpler stages so that the smelting and pouring processes can be completed in just a matter of hours. Meanwhile, the hydrometallurgical method, namely aqua regia, has issues with process speed, where several stages, including leaching, denoxing, precipitation, and smelting, require time individually, so that when accumulated, they result in a total time of several days for one batch. Of course, this

can slow down the production rate and potentially become a bottleneck on the production line.

### 3.2 Cost Analysis

The cost analysis in this study was conducted to compare the economic feasibility of hydrometallurgical (aqua regia) and pyrometallurgical (direct melting) methods based on Capital Expenditure (CAPEX), Operating Expenditure (OPEX), and the economic benefits of increased recovery. All cost values are presented in USD.



**Fig. 2.** Operational expenditure and capital expenditure comparison

#### 3.2.1 Capital Expenditure (CAPEX)

In general, hydrometallurgical processes, especially aqua regia, require lower initial investment with an estimated CAPEX of USD 17,905. This cost includes gold refining tumbler equipment, steam generators, and ventilation systems. On the other hand, the implementation of pyrometallurgical methods with direct melting also requires a large initial investment with an estimated CAPEX of USD 70,635, which mainly comes from the need for a high-temperature furnace and an Air Pollution Control System (APCS) to control particulate emissions. However, the direct melting system is simpler in terms of operation.

#### 3.2.2 Operating Expenditure (OPEX)

The analysis of operating expenditure (OPEX) in this study was conducted using the same operational basis, namely the processing of 3 kg of polishing dust per batch, so that a fair comparison between the aqua regia and direct melting methods could be made. The OPEX components analysed included tools and consumables, direct labour, energy, and waste management.

Regarding the aqua regia method, total OPEX is recorded at USD 134.30 per batch. This value is mainly influenced by the high demand for direct labour. The aqua regia process does not take place in one stage, but consists of several steps that must be carried out

sequentially, starting from leaching, filtration, denoxing, precipitation, to drying and final smelting. In practice, one batch takes approximately two working days ( $\pm 16$  effective working hours) and involves three operators to ensure that the process runs smoothly and safely. These conditions make labour costs the largest contributor to the aqua regia OPEX structure. In addition, the presence of acidic liquid waste also adds to the operational burden as it requires special handling, although the nominal cost is not as high as labour costs.

In the direct melting method, the total OPEX obtained from operational data is in the range of USD 110.99 per batch, which is lower than aqua regia. The cost composition is significantly different. The main cost burden comes from energy and consumables, especially flux and heat energy to reach the melting temperature. Although energy consumption is relatively high, the overall process is much shorter and more concentrated. In practice, one batch can be completed in about 3 hours, and the entire process can be operated by two operators. The absence of wet chemical reaction stages and lengthy intermediate processes reduces labour requirements and makes them more stable from batch to batch.

In addition, another equally important factor is waste management. Acidic liquid waste from aqua regia is classified as hazardous waste, so the cost of neutralizing and disposing at cost of \$7.88 per batch. On the other hand, direct melting produces solid slag, which does not incur handling cost. In fact, if the slag can be utilized or sold as supplementary cementitious materials (SCMs) [15], it has the potential to become a new source of income.

**Table 2.** Comparison of operational performance and costs

Parameter	Hydrometallurgy (Aqua Regia)	Pyrometallurgy (Direct Melting)
Gold Recovery Rate (based on trial result)	97.08%	99.97%
Process Time/Batch 3 kg	2 days	3 hours
Capital Cost (CAPEX)	\$17,905	\$70,635
Energy Consumption	\$2.76	\$50.73
Tools & Consumables	\$27 (concentrated acid, urea, sodium metabisulfite)	\$49.5 (flux and copper)
Labour Requirement	3 operators (multi-step process)	2 operators (few process steps)

Waste Management Cost	\$7.88 (sodium hydroxide)	\$0 (potential for revenue from slag sales)
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### 3.2.3 The Impact of Recovery on Economic Performance

When viewed solely from the perspective of operational costs per batch, the difference between aqua regia and direct melting is not particularly striking. However, the picture changes when gold recovery rates are included in the calculation. Based on operational results, direct melting consistently yields a recovery rate that is approximately 2.89% higher than aqua regia.

On a monthly production scale, this difference in recovery is no longer marginal. With the amount of gold processed each month, the additional recovery is equivalent to an economic value of around USD 9,917 per month. This value comes purely from gold that was previously lost in the aqua regia process and can now be recovered, without the need for additional production capacity or new process stages.

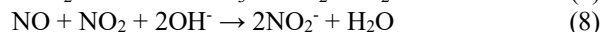
Direct melting does require a larger initial investment compared to aqua regia. However, the additional economic value generated from increased recovery means that the difference in CAPEX can be recouped in a relatively short period of time. With additional benefits of around USD 9,917 per month, the difference in investment between the two methods can be compensated for in around six months of operation.

### 3.3 Sustainability Analysis

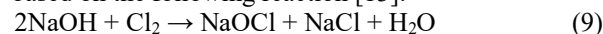
The hydrometallurgical process using aqua regia produces liquid waste in very large volumes. With an acid to ash ratio of up to 4:1, each kilogram of ash processed can produce at least 4 liters of acidic liquid waste. This waste is highly hazardous because it contains residues of nitric acid and concentrated chloride. It also contains high concentrations of dissolved heavy metals (such as Cu, Ni, Zn, Pb) originating from gold alloys and polishing compounds. Handling this waste requires a complex and costly multi-stage neutralization process, which ultimately also produces sludge [9]. In contrast, pyrometallurgical processes produce stable solid waste in the form of slag [10]. From the flux composition used in the process, there will be no toxic metal oxide such as PbO or Arsenic in the slag. Therefore, there is no need for treatment to the slag, and the slag can be sold as portland cement material [15].

Air emissions management also explains a fundamental difference between the two methods. The aqua regia produces highly toxic and reactive gases, such as nitrogen oxides (NO<sub>x</sub>) and chlorine gas [14]. The volatile and dispersive nature of these gases makes them difficult to capture, so they can easily pollute the air in the work area. To control these gases, a system called a wet scrubber is needed. Wet scrubber uses alkaline solution (NaOH) solution to absorb and neutralize acidic

fumes from aqua regia process. Nitrogen Oxides (NO<sub>x</sub>) gas composed of species of various oxidation stages such as NO, NO<sub>2</sub>, and HNO<sub>2</sub>. HNO<sub>2</sub> is readily soluble, while hydroxides in alkaline reacted with other NO<sub>x</sub> species to produce soluble NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup> based on these reactions [12]:



Chlorine gas is neutralized by NaOH creating sodium hypochlorite (NaOCl) and sodium chloride (NaCl) based on the following reaction [13]:



Pyrometallurgical processes, on the other hand, produce major emissions in the form of particulates (dust) from melting furnaces. Unlike fugitive gases, these particulate emissions can be managed very effectively through an integrated, multi-stage Air Pollution Control System (APCS).

**Table 3.** Comparison of sustainability aspects

Parameter	Hydrometallurgy (Aqua Regia)	Pyrometallurgy (Direct Melting)
Waste Form	Liquid (residual acid solution)	Solid (slag)
Waste Volume/batch	±19 L	±8 kg
Hazardous Characteristics	Residue from hydrochloric acid and nitric acid (Highly corrosive and toxic)	Silicon oxide and borate (Stable)
Air Emissions	Fugitive toxic gases	Particulate matter (dust)
Emission Control System	Wet Scrubber	Air Pollution Control System

### 3.4 Occupational Safety and Health (OSH) Analysis

In hydrometallurgical processes, the main risk is chemical hazards (fumes and effluent). Workers constantly interact with concentrated nitric acid and hydrochloric acid, which are highly corrosive and can cause acid burns if they come into contact with the skin or eyes. It is classified as low-risk hazard, requiring shower, medicine in first aid box and Personal Protective Equipment (PPE) [14]. However, the more serious and difficult risk to control is inhalation exposure. During the leaching process, corrosive acid vapours and highly toxic nitrogen oxide (NO<sub>x</sub>) and chlorine (Cl<sub>2</sub>) gases are released into the work

environment. NO<sub>x</sub> fumes are classified as extreme risk level that cause skin irritation and asphyxiation, requiring air ventilation, scrubber, NO<sub>x</sub> detector, and PPE [14]. In pyrometallurgical processes, the dominant risk shifts to physical (thermal) hazards. The main hazards are the potential for burns due to accidental contact with extremely hot furnace surfaces or from splashes of molten metal and slag during the pouring process which is classified as high risk, requiring fire resistant aprons and thermal gloves PPE [14]. The main inhalation risk is associated with solid dust during the raw material handling and flux mixing stages. However, this risk can be effectively managed by using local exhaust ventilation systems and appropriate respiratory PPE, such as respirators.

The transition from hydrometallurgy to pyrometallurgy fundamentally shifts the operational risk paradigm. The dominant hazards shift from invisible (gas and vapor) and difficult-to-control chemical risks to physical risks (heat) that are much easier to identify, localize, and mitigate. This shift is particularly important because it aligns with OSH hazard control principles, which always prioritize engineering controls (hazard isolation) over personal protective equipment (PPE). In practical terms, isolating heat sources through thermal insulation and physical shielding is a more reliable strategy than attempting to capture all fugitive gas emissions from chemical reactions in open vessels. Although both processes have potential hazards, the types of hazards in pyrometallurgy are easier to manage through an inherently safer design approach.

## 4 Conclusions

This comparative study concludes that although both aqua regia-based hydrometallurgical and direct melting pyrometallurgical methods are highly effective from a metallurgical standpoint for recovering gold from industrial jewellery polishing dust. However, when the evaluation goes beyond metallurgical aspects to include actual recovery, process time, economic, safety, and sustainability, the differences in performance between the two methods become more apparent.

Some key points that can be concluded are as follows:

1. Gold Recovery: Direct melting provides higher recovery, with a difference of approximately 2.89% compared to aqua regia. On a monthly production scale, this increase in recovery results in an additional economic value of approximately USD 9,917 per month from gold that was previously unrecoverable.
2. Operational efficiency: The aqua regia process takes approximately two working days ( $\pm 16$  hours) for one batch, while direct melting can be completed in approximately 3 hours. This difference has a direct impact on production throughput and reduces potential bottlenecks in daily operations.
3. Operating costs (OPEX): The aqua regia method has an OPEX of approximately USD 134.30 for processing 3 kg of polishing dust per batch, while direct melting is in the range USD 110.99 per batch. This gap of cost is influenced by longer processing

time and greater labour requirement of the aqua regia method.

4. Initial investment (CAPEX): The aqua regia method requires a CAPEX of approximately USD 17,905, while direct melting requires a larger investment of approximately USD 70,635. However, the additional economic value generated from the increased recovery in direct melting makes it possible.
5. Waste management and work safety: In field operations, the difference in waste management between aqua regia and direct melting is quite clear. In aqua regia, the waste produced is acidic liquid. This waste is not easy to be disposed of immediately and must be further processed. During the process, operators also deal with chemicals and possible gases, so safe working practices are highly dependent on procedures and supervision. In direct melting, the waste produced is solid slag. This slag is more stable and easier to handle. The risks are more related to heat and high-temperature equipment. These types of risks are generally easier to control because they can be anticipated in the design of the equipment and emission control systems. In daily practice, these conditions make the direct melting process easier to control.
6. Circular Economy: It opens up opportunities for the processing of waste (slag) into valuable products, in line with the principles of closed-loop production and SDG 12.

Based on these findings, it is strategically recommended for the jewellery industry to consider investing in and transitioning to modern pyrometallurgical technologies (direct melting) equipped with effective air pollution control systems. This method not only offers higher gold recovery and shorter processing times, but also provides better economic performance, despite requiring a larger initial investment. With the added value of increased recovery, the investment difference can be recouped in a relatively short period of time. In the context of the jewellery industry, these conditions make direct melting a reasonable and realistic choice for the medium to long term, especially for companies that want to simplify processes, reduce operational risks, and strengthen the industry's commitment to sustainable and responsible manufacturing practices, which are key factors for long-term success in an environmentally conscious global market.

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