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Precious Metals Recovery Process from Electronic Boards: Case Study of a Non-Profit Organization (QC, Canada)

Caroline Blais [1,*], Anh Quan Le Dinh [2], Éric Loranger [3] and Georges Abdul-Nour [1]

[1] Department of Industrial Engineering, Université du Québec à Trois-Rivières,
Trois-Rivières, QC G8Z 4M3, Canada; georges.abdulnour@uqtr.ca
[2] Department of Electrical Engineering, Polytechnique Montréal, Montréal, QC H3T 1J4, Canada;
anh-quan.le-dinh@polymtl.ca
[3] Department of Mechanical Engineering, Université du Québec à Trois-Rivières,
Trois-Rivières, QC G8Z 4M3, Canada; eric.loranger1@uqtr.ca
* Correspondence: caroline.blais3@uqtr.ca

Abstract: The growth in the consumption of electronic products in recent years has resulted in increasing electronic device waste. At the same time, there is a decrease in the availability of raw metals required to produce electronic boards. Recycling through the recovery of precious and critical metals contained in electronic board waste is a solution, but the processes need to be safer for the environment. This paper presents the steps that lead to investment in the development of an eco-friendly and cost-effective process for recovering precious metals from end-of-life electronic telecommunications cards. Social organizations can also become involved in the recycling of electronic cards, thus enabling the integration of marginalized people into society. We examine the case of a non-profit organization whose mission is to help people living with mental health problems through the recycling of end-of-life telecommunication devices. This recycling process must operate within constraints specific to this organization and to the employment of people with mental health issues. The literature review showed that considering ecological and economic factors, the hydrometallurgical process appeared to be a logical choice.

Keywords: precious metals; electronics; recovery process; hydrometallurgy

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1. Introduction

Constant increases in the use of electronics devices have been observed in the last few years. Manufacturers must adapt their industrial processes to meet this increased demand and demand for personalization of products [1,2]. Moreover, they need to consider the evolution of technologies and add new functions to enable enhanced human–machine interaction, provide consumers with a better experience and remain competitive on the market [3]. This quick technology turnover is one of the main causes of the reduction in the active life of electronic devices before they become obsolete [4]. Electronic waste was estimated at 53.4 million metric tons in 2019. This amount will reach 74 million metric tons by 2030 [5].

Among the proposed solutions is the development of eco-friendly processes to recover precious metals from electronic end-of-life devices, which are also called "urban mines". Indeed, a natural ore mine can produce 5 g of gold (Au) per ton of ore, while 200–250 g Au can be recovered from the same mass of computer boards (300–350 g Au/t for mobile phones) [6].

The aim of this research is to outline the steps involved in developing an economical and sustainable process for recycling precious metals that aligns with the mission and goals of a non-profit organization. The process development steps will be demonstrated through the case study of a non-profit organization based in Canada (Quebec). This paper, based on a literature review, presents the following: a comparison and selection of the most suitable existing processes; the selection and prioritization of the metals to be recovered; and finally, identification of the organization's process selection criteria.

2. Literature Review

Among the numerous articles written on the recovery of precious metals from electronic cards, particular attention has been paid to the main existing processes and their characteristics as well as to the choice of metals to be extracted as a priority because they determine the operating conditions of the process. The data collected are briefly described in this section.

2.1. Existing Processes

The first step is to examine the main existing processes, such as biometallurgy, pyrometallurgy and hydrometallurgy, whose advantages and limitations are known, comparing them based on a literature review. These processes could possibly be adapted to develop a new, more eco-friendly and cost-effective process.

2.1.1. Biometallurgy

Biometallurgy is a process for extracting metals from waste or mines using biological systems such as plants and microorganisms [7]. Unlike other processes, the solubilization of metals occurs mainly indirectly. The secondary products metabolized by organisms during the reduction of nutrients in their environment are used for the leaching of metals. For example, in the recovery of gold from printed circuit boards (PCBs), a cyanide leachate is produced by *Chromobacterium violaceum* through a secondary metabolite, hydrogen cyanide (HCN). HCN is produced when the amino acid glycine is transformed by the enzyme HCN synthase [8]. Chemolithoautotrophic microorganisms, such as *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans*, or metal-resistant actinobacteria, such as *Streptomyces* genera, are also used in the bioleaching of metals [7,9].

Bioleaching is a promising and sustainable process, which is both economical and environmentally friendly compared with pyrometallurgy and hydrometallurgy. However, this process faces several challenges such as a reaction time measured in days and lower recovery rates of precious metals compared with other processes, even when operating conditions are optimized [10,11]. Pradhan and Kumar (2012) achieved a 69.3% gold (Au) recovery rate after 7 days using *Chromobacterium violaceum* [12]. In their experiments, Argumedo-Delira et al. (2019) reported a maximum Au recovery of 56% using a mix of fungus after 12 to 16 h of reaction time [13].

2.1.2. Pyrometallurgy

Pyrolysis is the thermochemical decomposition of organic materials at high temperature in the absence of oxygen. This process leads to changes in the physical phase and chemical composition of the materials. In addition to metal products (slag), there is formation of gases, liquid products (oils) and carbon-rich solid residues called coke [14].

In the case of the metal recovery from printed circuit boards (PCBs), pyrolysis is carried out at a temperature of around 1200 °C. The molten materials are vigorously mixed by the gases produced during the process. This stirring is necessary to reach the rapid equilibrium of the fusion reaction. At the end of the operation, the molten metal and the coke are taken from the bottom of the furnace. Copper (Cu) is the main metallic element present in the solid fraction. Refining and electrolysis allow its recovery, and precious metals are extracted from the anode sludge [14,15].

Researchers have studied the composition of the solid fraction following pyrolysis of electronic devices. As expected, Cu was the metallic element found at the highest concentration (% weight) in cell phones (12.4%) and electronic boards (36.4%). In these PCBs, precious metals, such as silver (Ag) (0.16%), Au (0.03%), and palladium (Pd) (0.01%), were also recovered [16].

One advantage in pyrometallurgy is the reuse of molecules from the decomposition of organic matter during processing. For example, gases are used for energy recovery and precious metals can be used as raw materials in new products. Also, pyrolysis significantly reduces the volume of residue produced at the end of the process [17]. Moreover, combined with mechanical methods, this process could increase the efficiency of e-waste recovery [14].

2.1.3. Hydrometallurgy

Hydrometallurgy is the extraction of precious metals by leaching in an acid or alkaline medium. This process requires mechanical pre-treatment of electronic wastes (crushing, grinding, etc.), dissolution of the metals with an appropriate leachate, purification of the enriched solution, and recovery of the leached elements [18]. The targeted metals are then extracted from the solution using different techniques such as precipitation, absorption, ion exchange, electrowinning, or solvent extraction [7].

Hydrometallurgical processes offer several advantages: high metal recovery rates, relatively low investment and operating costs, possible use in small-scale applications, and reduced environmental impacts [19]. Various reagents can be used as a leachate depending on their characteristics. The most common are described in Table 1.

Table 1. Advantages and limitations of most common reagents used in hydrometallurgical processes.

Reagents	Advantages	Limitations	Authors
Cyanide CN^-	• Selectivity for Au • Recovery rate for Au, Ag and Pd from mobile phone PCBs > 90%	• High environmental toxicity of solvent and by-products • Workers' health risks	[20,21]
Aqua regia 1 HNO_3:3 HCl	• Typically used for dissolution of Au and platinum group metals • Easy to use • Low cost • Quick reaction times	• Not selective • Loss of precious metals → formation of silver chloride precipitate • Corrosive and oxidative conditions • Formation of toxic chlorine gases	[22,23]
Iodine I_2	• High selectivity for precious metals • High Au recovery rates > 99% • Quick reaction times • Low toxicity • Absence of corrosive effects	• Very high reagent costs	[23–25]
Chlorine Cl^-	• High extraction rates • AuCl complex easy to separate and recover Au • Good Pd recovery rate • Possible to regenerate and reuse the HCl	• Corrosive and oxidative conditions • Volatile gas formation • High reagent costs	[14,20,23]
Thiosulphate $S_2O_3^{2-}$	• Selectivity for precious metals • Non-toxic • Alkaline medium	• Very slow reaction times • Requires addition of additives → great reagents consumption	[23,26]
Thiourea $CS(NH_2)_2$	• Quick reactions • Relatively good efficiency	• Requires addition of oxidant • Effectiveness depends on reagent concentrations and pH • Solution is unstable • Suspected carcinogen	[20,23,27,28]

Other reagents, e.g., lime sulphur synthetic solution (LSSS) or methylsulfonic acid (MSA), have been used as lixiviants, but the results regarding the recovery of gold and precious metals have been contradictory or inconclusive depending on the studies [23,29].

2.1.4. Processes Comparison

Comparing the main characteristics of biometallurgy, pyrometallurgy and hydrometallurgy processes could help choose a more ecological, sustainable, and efficient process for recovering precious metals from electronic cards. The advantages and limitations of these three processes are summarized in Table 2.

Table 2. Comparison of advantages and constraints of processes in precious metal recovery from electronic waste.

Processes	Advantages	Limitations	Authors
Biometallurgy	• Sustainable and environmentally friendly • Low investment and operating costs	• Long reaction time (a few days). • Lower precious metal recovery rates than other methods.	[12,13]
Pyrometallurgy	• Applies to all types of electronic wastes. • No pre-treatment needed but this step can improve efficiency. • Requires few steps. • Significant residue reduction. • Short reaction time.	• High investment and operating costs. • Iron and aluminium recovery is very difficult. • Use of flame retardants in PCBs leads to the formation of toxic gases such as dioxins and furans during pyrolysis. • Formation of volatile metals and dust released into the environment. • Recycling of plastics not possible because it replaces coke as an energy source. • Additional processing is required for the selective recovery of precious metals (e.g., hydrometallurgy)	[14,30–35]
Hydrometallurgy	• High selectivity. • Works even at low feeding capacity. • Low investment costs. • Less environmental impact.	• High consumption of reagents and water that need to be treated before disposal. • Pre-treatment of waste required for good efficiency. • Multi-step processing. • Reaction time longer than pyrometallurgy.	[23,30,32,36,37]

2.2. Metals to Prioritize

Part of the profitability of a process comes from the profits made from the resale of the recovered metals. But the quantities of precious metals are not the same for all types of electronic cards. Therefore, it would be interesting to verify whether the prioritization of precious metals determined for one type of PCB, such as those from computers or mobile phones, can be transposed to other types of less-studied electronic cards e.g., telecom PCBs.

2.2.1. Criteria

In the absence of a classification model, specific evaluation criteria, such as the economic value of the metals and the current price of the precious metals on the market per troy ounce (oz t.), enable the assignation of a different value to each of the targeted precious metals, considering market volatility, and would thus promote metal recovery.

2.2.2. Precious Metals in PCBs

To protect their company's interest, most electronics manufacturers have very strict confidentiality agreements. They keep the composition and distribution of the precious metals on their electronic boards secret. Having a better knowledge of the distribution of precious metals in the different types of PCBs would facilitate the recycling of these metals by targeting the richest parts and components, which would make the process more efficient [38].

Huang et al. (2022) studied the composition and distribution of precious metals in ten motherboard models that differed by manufacturer, design, and year of manufacture. They established that the average quantities of precious metals per ton of cards were 39.19 g Au/t, 22.89 g Ag/t and 0.09 g Pd/t [38].

Holgersson et al. (2018) studied the composition of telecom PCBs of modems, routers and hubs that were manufactured between 2004 and 2010 and were obtained from e-waste in Sweden. The precious metal contents found were 199 ppm Au, 1213 ppm Ag and 19.5 ppm Pd [39]. Also, they determined the precious metal composition of mobile phone and smartphone PCBs manufactured from 2001 to 2010 and from 2004 to 2013, respectively. The mobile phone PCBs were composed of 2640 ppm Ag, 1051 ppm Au, 119 ppm Pd and 4.9 ppm platinum, a composition similar to that of the smartphone PCBs, whose precious metal contents were 2773 ppm Ag, 1083 ppm Au, 55.4 ppm Pd and 0.8 ppm Pt.

2.2.3. Economic Analysis of Precious Metals

The economic value of precious metals recovered from circuit boards can be calculated using the following formula:

$$B = \sum \mathrm{M_p} \times \mathrm{P} \tag{1}$$

where B is the total economic value calculated by the sum of the average concentrations of precious metals per ton of PCBs, $\mathrm{M_P}$, multiplied by the average annual cost of precious metals P in a certain period [38]. Using this formula, estimating the gross profit from the recovery of precious metals from one ton of electronic cards was possible. The data were obtained from the literature and the results are presented in Table 3.

Table 3. Estimation of the economic value of recovered precious metals according to the type of the PCBs.

Precious Metals	Precious Metals Content				Annual Average Prices 2023 ***	Economic Value Estimated			
	Telecom PCBs M_{p1} (g/t) *	**Mother-Boards M_{p2} (g/t) ****	**Mobile Phone PCBs M_{p3} (g/t) ***	**Smartphone PCBs M_{p4} (g/t) ***	**P (USD/oz t.)**	**Telecom PCBs B_1 (USD/t)**	**Mother-Boards B_2 (USD/t)**	**Mobile Phone PCBs B_3 (USD/t)**	**Smartphone PCBs B_4 (USD/t)**
Au	199	39.19	1051	1083	1942.99	12,432.62	2448.41	65,661.75	67,660.96
Ag	1213	22.89	2640	2773	21.75	912.16	17.21	1985.25	2085.26
Pd	19.5	0.09	119	55.4	1338.69	839.37	3.87	5122.33	2384.68
					Total $_{B1\to B4}$:	14,184.16	2469.50	72,769.33	72,130.91

Note: 1 oz t. is approximately 31.10 g, and 1 t is 1000 kg or 1 metric ton. * Data from Holgersson et al., 2018 [39], ** Data from Huang et al., 2022 [38], *** Data from LBMA, https://www.lbma.org.uk/prices-and-data/precious-metal-prices#/table (accessed on 9 January 2024).

These results show that the various PCBs have different economic values, and this value depends on the specific contents of precious metals. Therefore, it is more economically advantageous to recover precious metals from the electronic cards of mobile phones and smartphones than from cards of other devices. Due to their relatively high content of gold, telecom PCBs have more economic value than motherboards, which suggests that recycling telecom devices could be profitable.

2.2.4. Prioritization of Precious Metals

The prioritization of precious metals can be determined based on the economic contribution of each. By comparing the proportion of every metal, it is possible to highlight the differences and thus determine the precious metal with most economic impact (see Figure 1).

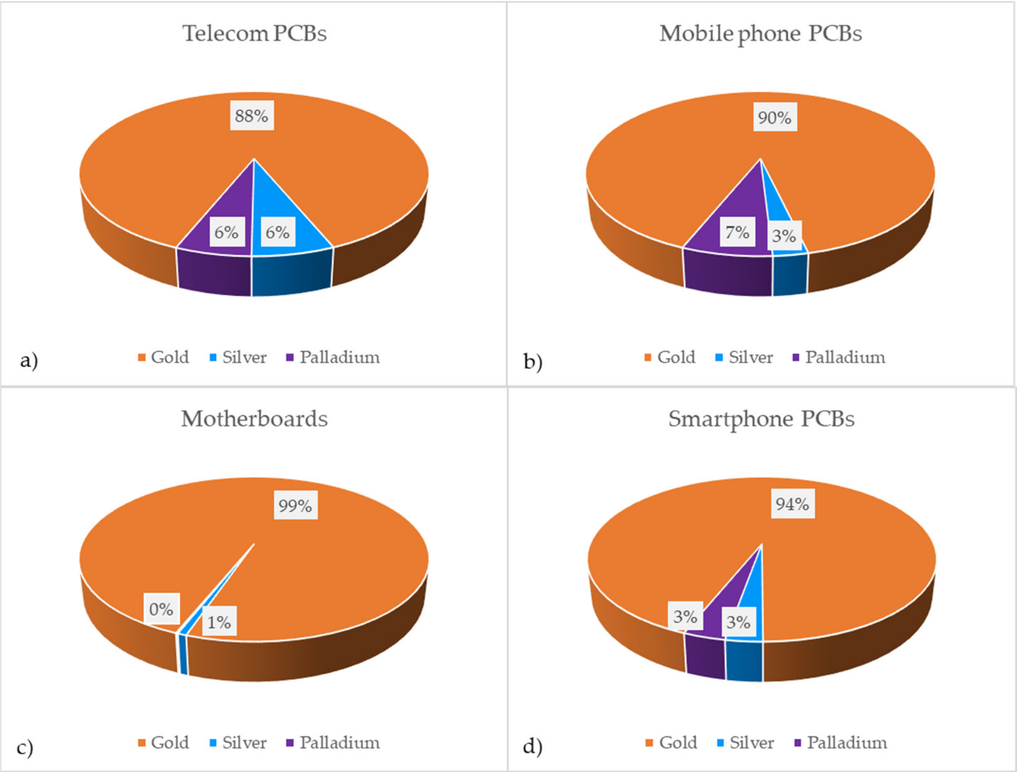

Figure 1. Total economic value (*B*) of precious metals in different types of electronic cards: (**a**) telecom boards, (**b**) mobile phone PCBs, (**c**) motherboards, and (**d**) smartphone PCBs.

Figure 1 shows that the gold has the greatest economic potential for the four types of PCBs. Despite its low price, silver is in second place for telecom boards and motherboards due to its high content, while palladium is in second place for mobile phones and smartphones (see Table 4).

Table 4. Prioritization of precious metals based on their economic contribution according to types of PCBs.

	Priority Order		
Type of PCBs	**#1**	**#2**	**#3**
Telecom	Gold	Silver	Palladium
Motherboard	Gold	Silver	Palladium
Mobile phone	Gold	Palladium	Silver
Smartphone	Gold	Palladium	Silver

By following these steps, a company wishing to develop a process for recovering metals from electronic cards could choose the process best suited to its situation. This hypothesis was tested by a case study.

3. Case Study

The case studied is a non-profit social economy organization whose mission is to promote the social and professional integration as well as the recovery of people with mental health issues. The organization has worked for several years as a recycler of end-of-life electronic and computer products for well-known companies in the telecommunication and internet sectors in Quebec, Canada. With their acquired knowledge on the recycling of devices and considering their wish to become more involved in environmental protection, the organization became further involved in the process of recycling materials by trying to develop an eco-friendly and cost-effective process for the recovery of precious metals. Likewise, the profits from precious metal recovery could provide the resources to help more people with mental health issues by offering them better jobs. The organization initiated some preliminary research which aimed to develop a forecasting model to estimate the quantities of electronic waste that will be generated in the future and to determine the criteria and sub-criteria for selecting the future process [40,41].

Other authors demonstrated the usefulness of work as an effective approach for the rehabilitation of people with mental health conditions [42]. Also, a study by Villotti et al. (2018) showed that the skills and abilities acquired after spending 12 months working in a social enterprise enabled people with serious mental disorders to reduce their perception of stigma, resulting in improved social inclusion [43]. In addition, occupational engagement assists in the recovery process by providing routine and structure, life purpose, a sense of belonging, a sense of self esteem, autonomy, and hope [44].

3.1. Identification of the Organization's Criteria

The process that will be designed must respect the following criteria:

- The process is eco-friendly, sustainable, and safe for people (workers, transporters, suppliers, etc.).

This is the most important criterion for the organization. The choice of the process was evaluated through the environmental criteria indicated in Table 5.

Table 5. Comparison of environmental impacts of precious metal recovery processes from electronic boards.

Environmental Impact Criteria	Biometallurgy	Pyrometallurgy	Hydrometallurgy
Energy	Low energy consumption.	High consumption of energy: furnace must reach temperature of around 1200 °C.	Less energy needed than pyrometallurgy [14].
Reagents	Addition of essential elements to support bacterial growth [45].	Further treatment needed to recover precious metals (e.g., hydrometallurgy)	High consumption of reagents but some can be reused or regenerated. High water consumption.
Harmfulness	Production of less toxic residues than pyrometallurgy and hydrometallurgy [13].	Production of harmful gases from 250 °C [34]. By-products such as dioxins and furans are toxic for humans [46].	Some reagents can be corrosive. Used reagents and water need treatment before disposal to protect environment.

It should be noted that the process will be implemented in Quebec (Canada) where the cold winter conditions encountered can have a great influence on the energy consumption required to maintain process temperature conditions.

Concerning safety, the non-profit organization already has solid experience in manual dismantling of electronic telecom devices. The protection, training and safety of workers dealing with mental health issues are currently managed through the application of an Environmental Health and Safety (EHS) system. This system also includes all the measures applied to ensure environmental protection. An external certification body is mandated to verify the compliance with this system through an annual audit, and compliance is attested by obtaining and maintaining international certification standards "The Sustainable Electronics Reuse & Recycling Standard v3" (R2v3).

The chosen process must, therefore, be integrated into the EHS system in place and meet current laws, as well as strict R2v3 certification standards for the protection of the environment and workers.

- The process is technically feasible.

The type of process selected must have previously demonstrated its feasibility through the efficient extraction of precious metals with an expected recovery rate greater than 80%. This value is the minimum threshold to guarantee the profitability of the process for the non-profit organization. However, the processes that demonstrate very good precious metal recovery efficiency are generally operated under conditions that could compromise the safety and health of workers suffering from mental health issues. The operating conditions of the chosen process could be adjusted to further protect workers, but the recovery yield of the metals of interest would be reduced as a consequence of this compromise.

In addition, the selectivity for the prioritized metals is an important factor to consider. Indeed, greater selectivity of a process for the recovery of precious metals improves their quality and purity, which has a positive impact on the metal's resale price.

- The process is effective even at low feeding.

Also, the process chosen must be efficient at low capacity because the organization's mission remains its priority. This implies that manual dismantling of the devices is prioritized, allowing a greater number of people to participate, and be helped but also limiting the quantity of electronic cards that can be extracted. Indeed, the tasks performed by workers at the organization consist mainly of the manual dismantling of telecom devices and sorting the components to the appropriate downstream recycling. Although these tasks are repetitive and the workers' dexterity improves over time, manual dismantling cannot process quantities of electronic boards similar to those processed by automated process.

- The process is cost effective.

The investment and operating costs, as well as the energy costs, resulting from implementation and operation of a precious metal recovery process can be substantial, particularly for a non-profit organization, and constitute another important factor in process selection. Table 6 shows the investment and operating costs for three different processes.

Table 6. Evaluation and comparison of investment and operating costs according to the type of process for recovering gold from WEEE.

Process	**Plant**	**Quantities of e-Waste**	**Costs**		**Authors**
			Investment	**Operating**	
		t/Year	**USD**	**USD/Year**	
Pyrometallurgy	Umicore, Belgium	250,000	212 million	10 million **	[47]
	Horne Smelter and Refinery CCR, Canada	100,000	n/a	51 million	[48]
Hydrometallurgy	Pilot Unit, Serbia	8.94 *	149,000	144,000	[49]

* Calculated from simulated article data: 100 kg WEEE/batch at a concentration of 440 ppm Au. According to gold prices on 29 October 2010 (LMBA, 1336.75 USD/oz t.). ** Costs of 106 million USD between 1995 and 2006.

3.2. Choice of the Process

A limiting element in the choice of process is the supply of feed materials. As mentioned previously, the social mission of the organization remains the priority, and the consequence is the low quantities of incoming materials compared with other automated mechanical processes. Based on the organization's data related to dismantling and recycling of telecom devices received in 2019, the estimated quantities and the potential revenue from recovered precious metals are presented in Table 7.

These estimates help in choosing the most suitable process considering the non-profit organization's constraints.

From all the elements presented, it is possible to assign a rating based on the criteria established by the organization for each of the processes according to their advantages and limitations (Table 8).

Table 7. Estimates of the quantities and potential profits of precious metals from end-of-life modems and routers received by the non-profit organization in 2019.

Precious Metals	**PCBs Weight**		**Precious Metal Content**			**Annual Average Prices 2023 ****	**Total**
	Modems	**Routers**	**Telecom PCBs**	**Modem PCBs**	**Router PCBs**		
	kg	**kg**	**(g/t) ***	**g**	**g**	**(USD/oz t.)**	**USD**
Gold	34,489	13,095	199	6863	2606	1942.99	591,593.96
Silver			1213	41,835	15,884	23.39	43,404.30
Palladium			19.5	673	255	1338.69	39,940.77

* Data from Holgersson et al., 2018 [39], ** Data from LBMA, https://www.lbma.org.uk/prices-and-data/precious-metal-prices#/table (accessed on 9 January 2024).

Table 8. Comparison of processes according to the organization criteria.

Non-Profit Organization Criteria	**Evaluation of Criteria in Favor of the Process**		
	Biometallurgy	**Pyrometallurgy**	**Hydrometallurgy**
The process is eco-friendly, sustainable, and safe for people	+	−	+
The process is technically feasible	−	+	+
The process is effective even at low feeding	+	−	+
The process is cost effective	+	−	+

Biometallurgy is a process that has minimal impact on the environment and worker safety. It operates at low capacity, requires low investment, and has minimal operating costs. However, its use is limited due to the very long reaction times and low recovery rates of precious metals.

The pyrometallurgical process is considered the most harmful to the environment and worker safety due to the production of toxic gases and by-products, as well as its high energy consumption. To improve precious metal recovery efficiency, additional treatments such as hydrometallurgy are required to properly separate the metals, which results in elevated consumption of reagents. Furthermore, the process is unsuitable for the organization due to its high investment and operating costs, as well as its requirement to operate at high capacity to be profitable.

Regarding the hydrometallurgical process, its environmental impact is greater than that of biometallurgy but still lower than that of pyrometallurgy. The impacts on the environment and health, selectivity for the metals of interest, recovery efficiency of precious metals, and reaction times depend on the chosen reagents. Among the reagents listed in Table 1, iodine and thiosulfate are less harmful to the environment and worker health than cyanide and aqua regia. Chlorine may also be a viable option, but only with the use of appropriate equipment to prevent corrosion and treat harmful gases released during the reaction. Additionally, this reagent can be regenerated and reused, which reduces waste quantities and operating costs. The decision of the non-profit organization to eliminate thiourea was primarily based on its instability, classification as a suspected carcinogen, and suspected toxicity for reproduction.

The results of the criteria evaluation show that the hydrometallurgical process is the most suitable precious metal recovery process for the organization studied.

4. Conclusions

Often marginalized, people struggling with mental health issues do not have the same opportunities as others to learn and work in specialized fields. The objective of the non-profit organization studied is to design a new ecological and efficient process for recovering precious metals to help a greater number of these people by offering them specific training and jobs where their needs will be respected. To select the most suitable treatment process, an analysis of existing processes was carried out based on a literature review, as well as a prioritization study of the precious metals to be recovered. Analysis of the data shows that a hydrometallurgical treatment would be the most appropriate to the needs of this organization.

However, the choice of reagents and different operating conditions will require additional studies. The next steps, mainly carried out in the laboratory, will consist of characterizing the metal content of electronic board samples and choosing pre-treatments to prepare these boards before testing leaching reagents and operating conditions. In addition, it is necessary to find a method to recover precious metals from leaching solutions. The results from each step of the process will be evaluated, and the conditions will be selected to meet the environmental, technical and economic criteria of the organization.

Environmental protection concerns and the involvement of people with mental disorders are very important issues for the organization. The future process design will allow them to participate in this mission and also help them progress in their rehabilitation process.

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