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The use of an electrogenerative process as a greener method for recovery of gold(III) from the E-waste

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ABSTRACT

In this present work, an electrogenerative flow-through reactor with an activated reticulated vitreous carbon (RVC) cathode was developed and used in recovering gold from an E-waste. The system resulted in more than 99% gold being recovered within 2 h of operation for 100 mg L^{-1} of initial gold(III) chloride concentration. Besides, the flow cell system in series shows around 98% gold being recovered within 4 h. From three different cathodes studied, activated RVC serves as the best cathode material having the highest recovery rate with more than 99% of gold from E-waste being recovered in 2 h of operation. It has an exceptional high void volume, highly porous surface structure, rigid structure and low resistance to fluid flow. It can be seen that the developed electrogenerative method is environmentally friendly and could recover the gold fully (>99%), even at a low concentration of gold. Finally, the morphology of gold deposits on an activated RVC cathode was also investigated.

1. Introduction

Economists assume that the price of gold, though uncertain, is estimable. These approach the estimation like that of any other commodity with rising production costs. A first approximation to the gold market trend over the past decades is best gained by viewing the data reported by Shafiee and Topal [1]. Gold is a precious metal well known for its singular beauty. It is widely used in the electronics industry because of its excellent electrical conductivity and high corrosion resistance. In addition to its wide application as decorative gold plating in the jewellery industries, electrodeposited gold is extremely important.

Electronic waste (E-waste) can be described as discarded electrical and electronic equipment such as unwanted computers, office electronic equipment and entertainment device electronics [2]. This includes used electronics, which are intended for reuse, recycle or disposal. The resources contained in E-waste are numerous; however, these contain valuable and recyclable metals. Typical materials contained in E-waste are halogens, toxic elements, non-metals and metalloids, non-ferrous metals, precious metals and other minor substances such as plastics and glass [3].

Recycling or recovery of E-waste, especially the precious metals (e.g. gold, silver, platinum and palladium), is an essential issue not only from the recovery aspect of precious materials but also from the point of waste treatment, environmental pollution and adverse human health effects. There are seven major benefits that have been identified by the US Environmental Protection Agency (EPA) when using scrap iron, steel or other metals instead of using virgin metals or materials [4]. These benefits include reduction in pollution, saving in energy and reducing the potential hazards involved in the mining of the virgin materials, which are the main contributions towards the preference for recovering the E-waste.

The most common methods used in the recovery of gold from E-waste are hydrometallurgy, biometallurgy, pyrometallurgy, precipitation and recovery from leachants [5–17]. However, some of these methods involve using hazardous chemicals as stripping solutions, are less environmentally friendly, time consuming, consume excessive energy, could not recover low concentrations (<500 mg L^{-1}) and could not recover the gold fully. Thus, the push for better methods of gold recovery from E-waste is desirable, particularly methods that are less harmful to the environment and could recover the gold fully.

A cost-effective treatment system is needed to recover and remove heavy-metal ions, including gold from industrial process streams. There is a trend in the metal finishing and processing industries to operate in a closed-loop system [18]. The system is designed with complete recycling of excess reagents to ensure maximum utilization and minimal waste generation. The unique physical and chemical properties of gold have made it a key metal in industry. The current gold recovery systems (e.g. hydrometallurgy, biometallurgy and electrowinning) are not able to recover

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the gold fully. Therefore, there is a problem in the E-waste recycle industry because of the requirement to dispose of the liquor used to recover gold.

Cyanide-leaching processes have been used by the mining industry for over 100 years in the extraction of noble metals. Cyanide ion is the most established leachant for extracting gold from E-waste [19]. The conventional method to leach and recover gold is to use cyanide ions. However, because of its toxicity, much effort has been made to replace this gold–cyanidation process with suitable alternative lixiviants, such as thiourea [20], thiosulfate ion [21], sulfite ion and thiocyanate ion [22], ascorbic acid [23] and chloride ion media [2,24–27], which have been revived as a result of the major increase in the gold price and have stimulated new developments in extraction technology, combined with environmental concerns [28–31].

In chloride ion systems, however, the adsorbed species are reduced to metallic gold and for reversible adsorption other adsorbent materials are needed. Effective adsorption of gold(III), Au(III), on non-ionic polymeric adsorbents from hydrochloric acid solutions has been demonstrated in several studies. This property has been exploited in analytical chemistry [32,33]. There are several methods available for metal ion removal and recovery from process solutions. Among these techniques, precipitation is the most widely used because of its simplicity and cost effectiveness. The solution pH is adjusted to the optimum range for precipitating the metal as a hydroxide. Other methods have also been used for the recovery of gold, such as electrogenerative processes, cementation, ion-exchange resins, electrodialysis, electrowinning and biosorption [2,19,24,34–37]. However, high capital costs are involved in using ion-exchange resins, with strongly acidic and alkaline solutions being required to regenerate resins. Metal recycling deals mostly with dilute solutions with low amounts of the target metal. Hence, there are many factors that should be considered towards controlling the side reactions, thermodynamics and kinetics of the systems along with the operating cost. All systems mentioned above involve additional processes, such as use of costly materials, eliminating side reactions and preconcentration.

An ideal solution to this problem would be a system that recovers and recycles both metal and the water without any need for an external power supply because it is based on spontaneous chemical reactions. Therefore, an electrogenerative system or process was introduced that provides advantages with respect to ease of operation, scaling up the system as well as low operating cost. In this system, an electrochemical reaction takes place spontaneously in a divided cell where a more noble metal of high purity is deposited at the cathode and a less noble metal anode is oxidized, generating an external flow of current. It also allows for simplicity and for providing a clean electrochemical system that can be applied for fuel cells.

In our previous work, an electrogenerative system was presented as an alternative to the current recovery technologies. The recovery of Au(III) was carried out utilizing a batch cell using different cathode materials. Activated reticulated vitreous carbon (RVC) was the best cathode material among the electrodes studied with more than 99% of Au(III) recovered in 1 h of operation [36]. It is observed that RVC can recover Au(III) faster than the other types of cathodes because of its porosity and high surface area, which led to Au(III) being fully recovered within 2 h [36].

In metal recovery dealing with dilute solutions, three-dimensional carbon porous materials serve as perfect electrode materials owing to these following properties: large specific area, high porosity, chemical inertness, good electrical conductivity, good fluid permeability and mechanical resistance. RVC is an open-foam material of honeycomb structure composed solely of vitreous carbon. These allow operations with a low current density at the electrode–electrolyte interface, but with a relatively high current per unit of cell volume [38].

This paper aims at recovering Au(III) from an E-waste by an electrogenerative process utilizing a flow cell. The effect of using different cathodes in the recovery of Au(III) from chloride ion solution was also investigated. Here, an activation process was carried out for the three-dimensional cathodes to investigate the influence of tin–palladium activation towards reactor's performance, and finally the constructed system was utilized to recover Au(III) from an E-waste sample. In this work, few novel approaches have been performed. Firstly, recovery of gold from e-waste in a chloride media by using an electrogenerative flow-through reactor. This work has never been carried out and reported. Secondly, this system has been successfully used to recover the gold from main process stream of metals recovery process which is very difficult to recover/treat with conventional systems especially for metal at low concentrations. Thus this system eliminates several processes normally required to recover/treat gold at low concentrations such as preconcentration and precipitation. In addition, this system also eradicates the production of sludge associate with treatment of such wastes. Finally, the constructed system was successful in recovering of Au(III) from an E-waste sample up to 99% of its initial concentration within 2 h of operation.

2. Experimental

2.1. Chemicals and materials

Gold(III) chloride, $AuCl_3$ was obtained from Sigma-Aldrich and sodium chloride, sodium di-hydrogen phosphate and other chemicals used were in analytical grade. The anion exchange membrane used was Neosepta® AM-01 (Tokuyama Corp.). The anode was pure zinc (99% purity) of dimension 2 cm × 5.5 cm × 0.06 cm. The cathode materials used for gold recovery were porous graphite (PG) sheet (National Electrical Carbon Products, Inc., 2.0 cm × 5.5 cm × 0.4 cm), RVC 80 pores per inch (ppi) (The Electrosynthesis Co., 2.0 cm × 5.5 cm × 0.4 cm) and stainless steel (2.0 cm × 5.5 cm × 0.06 cm).

2.2. Cell configuration and experimental conditions

Fig. 1 shows a schematic view of the electrogenerative reactor. The system consists of an electrogenerative cell with two 250 mL reservoirs for anolyte and catholyte, a peristaltic pump and Sanwa Digital Multimeters. The cell consists of two stainless steel (F) and two Teflon endplates (E) with two electrolyte compartments which are separated by an anion exchange membrane (B) Neosepta® AM-1 (Tokuyama Corp.). Both anolyte (A) and catholyte (C) compartments have dimensions 6.5 cm × 1.5 cm × 1.0 cm and were mounted between two flow frames (D) which consisted of mesh turbulence promoters. There is an inlet and outlet to allow solutions to flow through the frames. To prevent leakage, the cell must firmly tightened by screws. The anode is zinc foil with dimension 2.0 cm × 5.5 cm × 0.06 cm. It is act sacrificial electrode. The zinc was soldered to a stainless steel current collector. The cathode materials used for gold recovery are RVC 80 pores per inch (ppi) (The Electrosynthesis Co.). The dimensions for RVC 80 ppi, PG and stainless steel used were 2.0 cm × 5.5 cm × 0.4 cm. The electrode was attached to a stainless steel current collector plate with conductive carbon adhesive (Leit-C). The galvanic components were sandwiched together with eight bolts and nuts. The electrolyte solutions were pumped into cell through the inlet opening at the bottom by a peristaltic pump (MasterFlex) and flowed out of the cell from the outlet at the top of the cell. In the system, the electrolytes flowed separately in a closed circuit through the