Recycling of gold from waste electronic components of devices

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Abstract−Tremendous generation of e-waste and its illegal recycling are causing immense threat to environment as well as the loss of precious metals. The present research reports a novel hybrid process for the total recovery of gold from small depopulated components of e-waste. Connectors and integrated circuits (ICs) liberated from printed circuit boards (PCBs) were pulverized and processed for gold leaching using 10 g/L sodium cyanide solution at 40 °C and mixing time 15 min, where more than 95% gold was found to be leached out in single stage. From the obtained leach liquor, gold metal was recovered by charcoal adsorption followed by heat treatment. The raffinate left after adsorption of gold was found to contain ~10 mg/L gold, which was also recovered using Amberlite IRA 400Cl at equilibrium pH 9.6 in 30 min maintaining aqueous/resin (A/R) ratio 25 mL/g. The raffinate solution was enriched to 882.41 mg/L and the solution was further processed to get metal/salt using cementation/ evaporation. Obtained leached residue is processed for non-ferrous metals recovery and finally disposed-off after treatment and TCLP test. The effluent left after leaching could be easily decomposed and treated in ETP using standard environmental procedure.

Keywords: E-waste, Recycling, Gold, Leaching, Ion-exchange

INTRODUCTION

Metallic gold is the most proficient and dependable conductor used in manufacturing of electronic parts of modern sophisticated electronic devices (cell phones, calculators, sensors, global positioning system units etc.) due to its excellent conductivity and anti-corrosion behavior. The presence of gold in such electronic gadgets enhances its conductivity, enables to carry very low voltages and minimizes the obstruction in the flow of current at contact points. Thus, connectors, switches, relay contacts, soldered joints, connecting wires, and connection strips of electronic items are usually made up of gold or its coating, making it highly reliable [1]. Manufacturing of such small electronic components involves several steps (electroplating, etching, rinsing, chemical and mechanical polishing (CMP)), which leads to production of enormous effluent. These effluents contain appreciable amount of valuable and precious metals. The concentration of gold in such effluent usually varies between 1 to 2,000 ppm, which is quite high compared to its high grade resources [2]. Lack of feasible technologies, awareness, and implementation of regulations as well as availability of cheaper manpower has rapidly accelerated the number of illegal electronic waste (e-waste) recycling sectors in developing countries.

According to USGS-2017 report, in the year 2015, global demand of gold in the field of electronics was 254 tons [3]. The increase in demand of electrical and electronic equipment in the market has also accelerated the generation of large amount of e-waste during their manufacturing as well as at their end of life [4]. The global generation of e-waste in 2016 was about 44.7 million tonnes [5,6],

and according to Scientific Reports, by 2030 the production of e-waste in developing countries is expected to be twice than that of developed countries [7]. Apart from containing precious metals like gold, electronic products also contain toxic and hazardous substances which have perilous impact on human life and environment. Therefore, proper treatment and safe disposal of e-waste entails scientific approach and proper management, in order to mitigate this emerging issue with the passage of time.

E-waste has emerged as a potential source of precious metals like gold. According to National Institute for Materials Science (NIMS) report 2015, ~16% of the world reserves for gold, i.e., more than 6,800 tons of gold are found in such urban mines [3]. Keeping in view, depletion of high grade mineral/ore of gold and its presence in significant quantity in such waste materials generated during the manufacturing of electronic items as well as at their end of life have turned the research interest towards process development for gold recovery from such secondary resources, which will not only conserve the natural resources but also reduce environmental pollution [8,9].

Various hydrometallurgical processes like leaching, precipitation, solvent extraction (SX) and ion exchange (IX) using suitable lixiviants, precipitants, organic extractants and resins, respectively, have been reported for the recovery of gold from various resources [10-12]. A process has been developed to recover gold from PCBs of e-waste using ammonium persulfate solutions. The process is environment friendly and leaching takes place by selective breaking of internal metallic bonds to release gold concentrate without grinding [13]. Bisceglie and co-authors studied the selective recovery of gold from waste and scraps using potassium cyanide and three-nitrobenzene-sulfonate [14]. A process was reported to recover gold from very dilute solution (parts per trillion) using Mn_2O_3 (nano structured) as adsorbent. The developed process was implemented

on seawater containing 0.1 and 1 mg/L of gold, which resulted in the recovery of 95% gold [15]. Shen and Xue in 2007 reported a process to selectively extract Au (III) from Pt (IV) in chloride medium by solvent extraction method using 2-hydroxy-4-sec-octanoyl diphenyl-ketoxime diluted in kerosene. Four counter-current stages were required for effective extraction of Au (III) into organic phase from the resulting raffinate left after Pd extraction [16]. A process to study the sorption behaviour of Au(III) from chloride solutions using Amberlite resins impregnated with Cyphos IL101 was also investigated [17]. Wei and team studied the selective recovery of gold from mixed metal solutions using Aliquat-336-impregnated alginate capsule [18]. During IX, the metal present in solution easily gets replaced with active sites of the resins. Subsequently, elution of the metal loaded resin is carried out using acidic or alkaline solutions to get pure solution. Some of the strong base resins like Purolite A-500, Dowex 21K and Dowex G-55 have been successfully used to adsorb gold from various aqueous solutions owing to their faster rate of reaction and excellent loading capacity [19,20]. Moreover, non-ionic resins, such as Amberlite XAD 2000, XAD-4, XAD-7 and XAD-8 resins, have also been used for the effective recovery of gold from dilute solutions [21-23]. The hydrophobic nature and exceptional adsorption properties of Amberlite XAD-7 and XAD-8 makes them highly effective as well as selective for the recovery of gold from waste solutions [24].

It can be concluded from the literature review that mostly hydrometallurgical processes (leaching/solvent extraction/ion-exchange or combination of one or two methods) have been considered suitable for the extraction of gold from various resources. Moreover, no complete process flow-sheet is available for total recycling of gold from small electronic components of e-waste. The novelty of this paper deals with waste material, feasible process and gold extraction from e-waste. Presented research reports a complete and novel process flow-sheet which is environmental and feasible for total recycling of gold as marketable product from small electronic components of e-waste and related effluent based on zero waste concept. The developed process has potential to be commercialized after some scale-up/pilot studies in continuous mode where the raffinate and the resin regenerated can be recycled back to the system. Implementation of the developed process on industrial scale will be an important step towards building a zero waste society.

EXPERIMENTAL

1. Raw Materials and Chemical Reagents

PCBs of waste sophisticated electronic devices and populated ICs (containing 0.03% Au) as well as raffinate/waste water (containing 10 mg/L Au along with Cu, Ag Zn) were used as raw material for experimental purpose to recover gold at laboratory scale. Sodium cyanide (NaCN) was supplied by May & Baker Pvt. Ltd, Dagenham, England, activated charcoal was procured from RFCL Limited, New Delhi, and Amberlite IRA 400Cl (strong base anion exchange resin) was supplied by Sigma & Aldrich Co. (USA). Laboratory grade chemicals, hydrochloric acid (HCl), sodium hydroxide (NaOH), thiourea $SC(NH_2)_2$, etc. used for experimental purpose, were supplied by Merck, India. All solutions were prepared by dissolving in distilled water.

2. Methodology

2-1. Sample Preparation

The waste PCBs of sophisticated electronic devices were collected and subjected to heat treatment for liberation of populated parts (ICs, MLCCs, diodes, resistors, etc.). The ICs were separated and pulverized using scutter cutter for size reduction, which will enhance the leaching efficiency. The outer layer of PCBs coated with gold (Fig. 1) and pulverized powder of ICs (Fig. 2) was used as raw material for experimental purpose.

2-2. Leaching Procedure

About 400 g of PCBs was used for surface leaching of gold in 1,000 mL of leachant. The leachant was prepared by dissolving sodium cyanide and m-nitrobenzene sulfonic acid sodium salt in distilled water maintaining pH in the range of 10-12. The leaching experiments were performed in an open top reactor at moderate temperature, whereas leaching of gold from the crushed ICs

Fig. 1. Outer layer of PCBs containing gold.

Fig. 2. Pulverized integrated circuits (ICs).

was carried out in a closed Pyrex glass reactor fitted with a condenser using a hot plate with a temperature controlling sensor (Make: Schott, Germany). Magnetic stirrer was used for mechanical agitation during the experiment. The percentage of gold leaching was calculated based on leach liquor analysis. The material balance was also checked by analyzing the leached residue. Satisfactory mass balance was obtained.

2-3. Adsorption Procedure

The leach liquor containing gold (~117 mg/L) generated at optimized condition was subjected to adsorption using activated charcoal. The slurry obtained was filtered and dried. Activated charcoal containing gold particles was burnt in the furnace at an elevated temperature to obtain gold metal.

2-4. Ion-exchange Procedure

Experiments for the adsorption of gold from raffinate (containing 10 mg/L Au) using Amberlite IRA 400Cl were carried out in conical flasks using a wrist-action shaker. After adsorption, filtration was done to separate the loaded resins from the raffinate. Elution of the metal loaded resin was achieved using a mixture of HCl and $SC(NH_2)_2$. To validate the results obtained from batch studies, adsorption of gold was in continuous mode using a vertical column containing weighed amount of resin and maintaining constant flow rate of liquid.
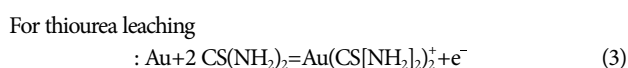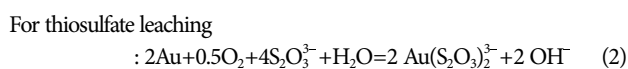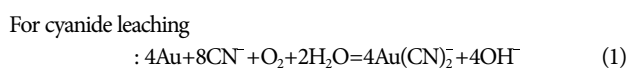
2-5. Analytical Procedure

The gold content in the leach liquor, eluate and raffinate were analyzed using Atomic absorption spectrophotometer (A Analyst 200, Perkin Elmer, USA). CL 46 (Toshniwal Inst. Mfg. Pvt. Ltd., Ajmer) pH meter was used to determine pH of various solutions during the experiment.

RESULTS AND DISCUSSION

Hydrometallurgical route comprising of leaching, adsorption and ion-exchange has been studied for the recovery of gold from waste electronic devices. The results obtained for the above mentioned are discussed below.

1. Leaching of Gold from Small Components of Electronic Waste

Leaching experiments were carried out to study the behavior of gold dissolution using various leachants: cyanide, thiosulfate and thiourea [25-27]. The overall reaction for gold dissolution using each leachant is presented below:

For cyanide leaching
$$: 4Au + 8CN^- + O_2 + 2H_2O = 4Au(CN)_2^- + 4OH^- \quad (1)$$

For thiosulfate leaching
$$: 2Au + 0.5O_2 + 4S_2O_3^{2-} + H_2O = 2\,Au(S_2O_3)_2^{3-} + 2\,OH^- \quad (2)$$

For thiourea leaching
$$: Au + 2\,CS(NH_2)_2 = Au(CS[NH_2]_2)_2^+ + e^- \quad (3)$$

Among all the above mentioned leachants, cyanide leaching was opted for selective leaching of gold from outer layer of PCBs as well as from the ICs owing to its ability to form a stable gold-cyanide complex without any required oxidant or catalyst other than water. In case of thiosulfate, dissolution rate of gold is quite slow, but acceptable leaching rates could be achieved using thiosulfate in the

presence of ammonia along with copper. Moreover, the principal concern associated with thiosulfate leaching is higher consumption of reagent during dissolution. On the other hand, though leaching rate is faster using thiourea, it is expensive and the stability of complex formed is very low [25,27]. Thus, further experiments for gold leaching were carried out using sodium cyanide. Various parameters such as effect of cyanide concentration, pH, temperature, and pulp density were studied and optimized in cyanide medium. Leaching of gold in cyanide medium usually takes place at higher pH. At low pH the amount of H^+ ions concentration in the solution increases, which combines with the CN^- ions to form hydrogen cyanide (HCN), thus resulting in the reduction CN^- ions available for leaching of gold. Maximum leaching of gold was achieved at pH ~11, keeping pulp density 400 g/L at 40 °C in contact time of 15 min. Experiments were also carried out by altering the cyanide concentration from 2 to 20 g/L at 40 °C, keeping pulp density 400 g/L for 30 min, to observe the behavior of gold dissolution. Leaching of gold was found to increase with the increase in cyanide concentration. About 95% gold was leached out using 10 g/L cyanide; further increase showed negligible increase in dissolution of gold. Thus, in view of low chemical consumption, 10 g/L was considered optimum for leaching of gold. Effects of temperature and time were also optimized for dissolution of gold. It was found that at low temperature (40 °C) effective leaching of gold was achieved compared to higher temperature, whereas the leaching of gold was found to increase with the increase in time from 2-15 min. More than 95% gold was leached out from the outer layer of PCBs and crushed ICs using 10 g/L cyanide at 40 °C in 15 min contact time (Fig. 3). All experiments were carried out in fume hood with proper ventilation following all safety measures.

2. Adsorption of Gold from Leach Liquor Using Activated Charcoal

The leach liquor containing gold was processed using the optimized condition for charcoal adsorption developed by our group at CSIR-NML [28]. Weighed amount of activated charcoal was added to the leach liquor and mixed continuously in atmospheric condition with sufficient supply of oxygen to efficiently adsorb gold
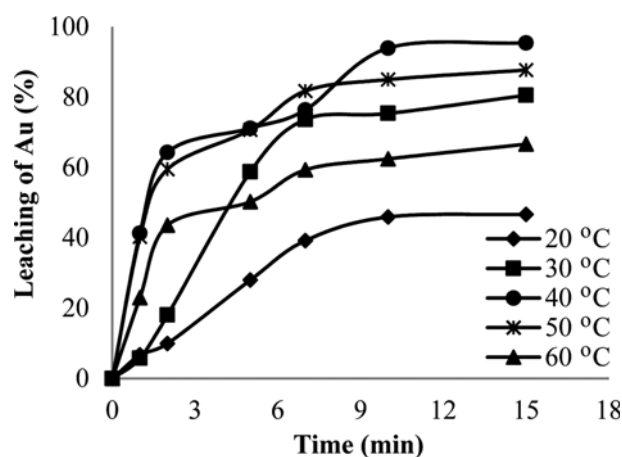

Fig. 3. Effect of temperature on leaching of gold at different time (Sodium cyanide concentration: 10 g/L; pulp density: 400 g/L; time: 15 min).
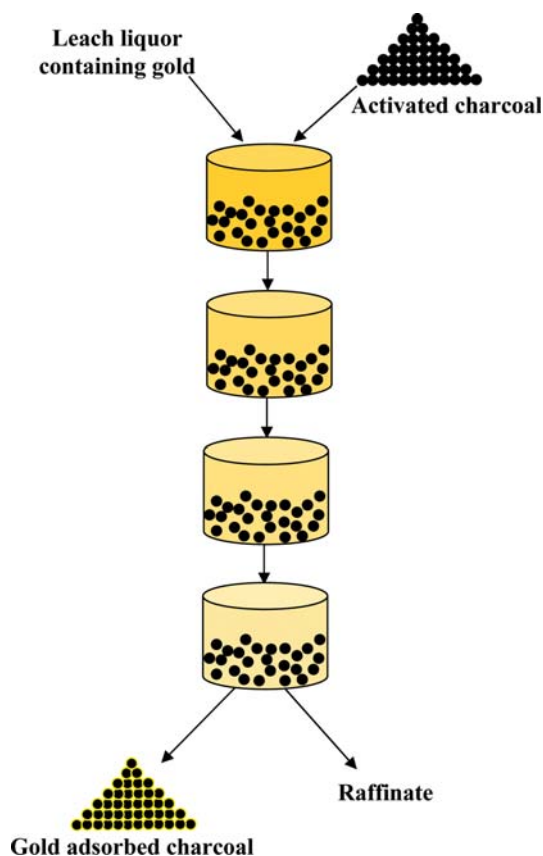
Fig. 4. Adsorption of gold on activated charcoal.

Fig. 5. Effect of pH (Aqueous: 10 mg/L Au; volume: 50 mL; wt. of resin: 2.5 g; time: 30 min).

from the solution. The complex formed $(Au(CN)_2)$ gets adsorbed due to the interaction of activated carbon and gold cyanide which consists of a weak bond that is unstable at high temperatures and makes the recovery of gold easy on burning at high temperature. The slurry obtained was filtered to separate the gold adsorbed charcoal from the raffinate. The charcoal containing gold was further dried and burned in a furnace at elevated temperature to recover gold metal. Fig. 4 shows the adsorption of gold from the leach liquor using activated charcoal and the raffinate obtained was further processed using ion-exchange technique to get enriched solution of gold.

3. Ion-exchange Study to Get Enriched Solution of Gold

The raffinate left after gold adsorption was analyzed and found to contain 10 mg/L Au along with Cu, Ag and Zn in traces. Keeping in view the loss precious metals in such dilute solution, batch experiments were done at laboratory scale to optimize experimental parameters for utmost adsorption of gold from raffinate as well as the result obtained were validated using column in continuous mode. Results obtained from the ion-exchange studies are discussed below.

3-1. Choice of Resin

Tulsion T42 (cationic) and Amberlite IRA 400Cl (anionic) were used to notice the selectivity of gold from the raffinate. Both the resins 2.5 g each and 50 mL of raffinate were taken in a conical flask and mixed with a wrist action shaker for 30 min. From the results obtained, it was observed that Amberlite IRA 400Cl was more
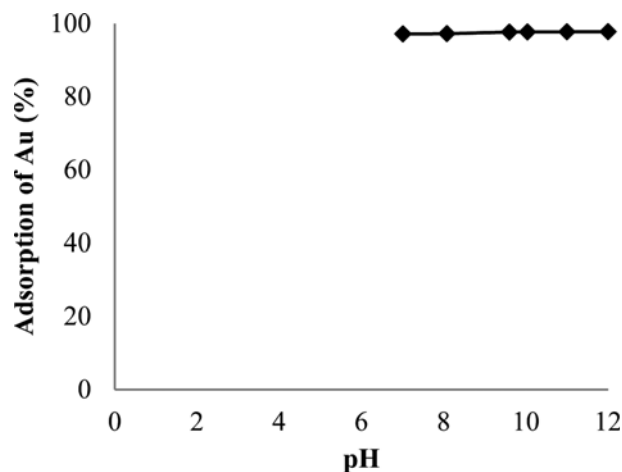
effective for the adsorption of gold (99.99%) compared to Tulsion T42 which showed negligible adsorption (~8.45%). From the above result, Amberlite IRA 400Cl was chosen as suitable resin to carry out further adsorption experiments.

3-2. Effect of pH

As pH of solution is one of the most important parameters in adsorption process, the studies for effect of pH on adsorption of gold by Amberlite IRA 400Cl were investigated. The results presented in Fig. 5 show that adsorption of gold was found to increase with increase in equilibrium pH. With an increase in equilibrium pH 7 to 12, the percentage gold adsorption increased from 97.16 to 97.77% for aqueous feed containing 10 mg/L Au. As the increase is negligible, thus change in pH of solution hardly affects the adsorption of gold from cyanide medium [29]. Maximum gold adsorption was obtained at equilibrium pH 9.6.

3-3. Role of Contact Time

Studies were carried out to optimize the minimum retention time required to attain equilibrium for adsorption of gold from the raffinate. 2 g of resin was mixed with 50 mL of the raffinate for different time intervals at room temperature. With the increase in contact time from 2 to 30 min, the adsorption of gold was found to increase from 90.34 to 99.05%. Further increase in contact time hardly affected the adsorption of gold; thus, 30 min contact time was optimized for further experimental purpose.

3-4. Adsorption Kinetics

To determine the mechanism for adsorption of gold, kinetic models were used to examine experimental results. Two different dilute solutions containing 6 mg/L and 10 mg/L Au were used to study the kinetics for adsorption of gold. Pseudo-first and second-order kinetic equations were calculated from experimental results obtained.

The equation given below represents the pseudo-first order of reaction [30-32]:

$$dq/dt = k_1 (q_e - q) \qquad (4)$$

where t is the mixing time, k_1 is the rate constant (min^{-1}), q and q_e are the amount of Au (mg/g) adsorbed onto the resin initially and

at equilibrium. Maximum adsorption at equilibrium, on applying boundary conditions (t=0 and q=0 to t=t and q=q_e), can be presented as Eq. (5):

$$\log (q_e - q) = \log q_e - (k_1/2.303)t \qquad (5)$$

Second-order kinetic for the adsorption of gold was also determined by fitting the results obtained in Eq. (6) [31,33,34]:

$$dq/dt = k_2 (q_e - q)_2 \qquad (6)$$

where k_2 is the rate constant for second-order reaction. Eq. (6) on applying boundary conditions (t=0 and q=0 to t=t and q=q_e) can be represented as 7:

$$t/q = 1/h + (1/q_e)t \qquad (7)$$

where h=$k_2 q_{e2}$ is the initial sorption rate.

The rate constants k_1 for pseudo-first order and k_2 for second-order were determined using the slope value obtained from the plot of log ($q_e - q$) vs t and t/q vs t, respectively, for both the aqueous solution containing 6 mg/L and 10 mg/L Au (Fig. 6(a) and (b)). In case of second-order reaction, the constant k_2 shows a linear relationship for both the aqueous feed containing 6 mg/L and 10 mg/L Au. The correlation coefficient in case of both the aqueous solu-
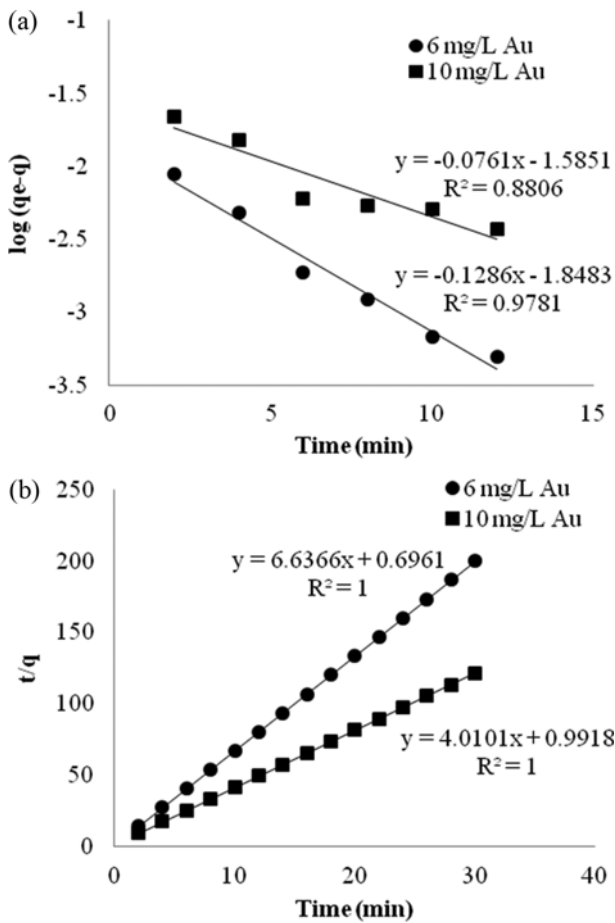
tion was found to be 1. As the values obtained were greater compared to first-order reaction, thus, adsorption kinetics for gold using Amberlite IRA 400Cl was found to follow second-order reaction.

3-5. Effect of Varying Resin Dose

Experiments were carried out to study the effect of resin dose on gold adsorption by changing the quantity of resin from 0.25 to 4 g in 30 min contact time. Adsorption of gold increased from 50.07 to 99.38% on increasing the amount of resin from 0.25 to 4 g as presented in Fig. 7. It is evident from the result that adsorption of metal from solution increases with the increase in amount of resin because the surface area or ion-exchange sites available for the exchange of solute increases [35-37].

3-6. Adsorption Ability of Amberlite IRA 400Cl

Studies were carried out to determine the adsorption capacity of Amberlite IRA 400Cl with 0.25 g of resin and 100 mL of raffinate. Fresh raffinate was repeatedly treated with the same resin till equilibrium was achieved for the adsorption of gold. About 2.1 mg/g of gold got loaded onto the resin in first contact. Further increase in the number of contacts resulted in the decrease of gold
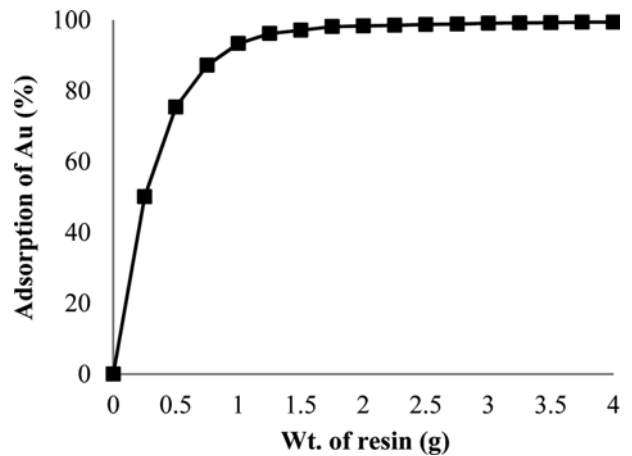

Fig. 7. Effect of varying resin dose (Aqueous: 10 mg/L Au; volume: 50 mL; Eq. pH: 9.6; time: 30 min).

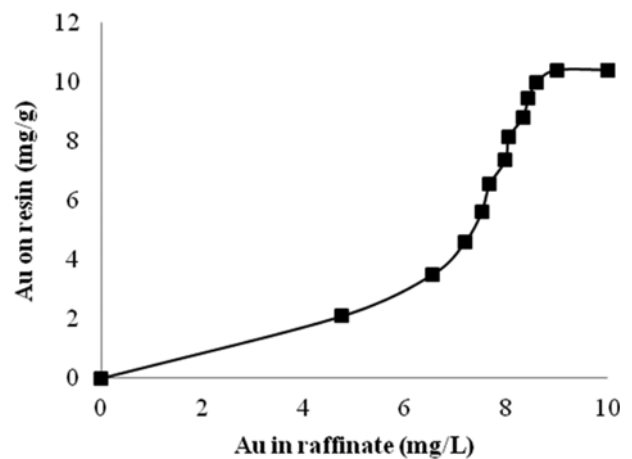Fig. 6. (a) Plot of first order reaction kinetics, (b) plot of second order reaction kinetics.

Fig. 8. Adsorption ability of Amberlite IRA 400Cl (Aqueous: 10 mg/L Au; volume: 100 mL; wt. of resin: 0.25 g; Eq. pH: 9.6; time: 30 min).

adsorption from the aqueous solution. This may be due to the decrease in available adsorption sites with each successive contact. The cumulative adsorption of gold in 11 contacts was found to be 10.38 mg/g. As a function of equilibrium, the amount of solute adsorbed per unit of adsorbent is presented in Fig. 8. Satisfactory mass balance was attained for the above experiment on calculating the results of raffinate left after gold adsorption and the eluate.

3-7. Adsorption Isotherms

Langmuir and Freundlich isotherms are most generally used to determine the adsorption phenomenon [35,38]. The results of batch studies for adsorption of gold were examined for both Langmuir and Freundlich equations. Langmuir model is based on the assumption that uptake of metal ions occurs on a uniform surface by monolayer adsorption without any interaction between adsorbed ions [38]. The Langmuir model is presented in linear form as Eq. (8):

$$1/q = [(1/k_l \cdot q_m)(1/C_e)] + (1/q_m) \qquad (8)$$

where C_e is the equilibrium concentration of metal (g/L), q is amount of metal adsorbed (mg/g), k_l is the Langmuir constant and q_m is the resin's loading capacity (mg/g).

Whereas the assumption for Freundlich model states that monolayer adsorption of metal ions takes place on a heterogeneous surface. Freundlich model can be described by the equation given below [39,40]:

$$q_e = k_f (Ce)1/n \qquad (9)$$

$$\log q_e = (1/n) \log (C_e) + \log k_f \qquad (10)$$

where k_f and n are Freundlich constants for adsorption capacity and adsorption intensity, respectively.

To validate the Freundlich and Langmuir isotherms, plots of log q_e vs. log C_e and 1/q vs. $1/C_e$ respectively, were calculated as shown in Fig. 9(a) and (b). The results obtained show that the Langmuir isotherm provides a better fit to the experimental data for gold adsorption over the Freundlich model.

3-8. FTIR Spectra of Amberlite IRA 400Cl

FT-IR spectra of fresh (original) and gold-loaded Amberlite IRA 400Cl resin were recorded for better understanding of the ion-exchange process and presented in Fig. 10. IR peak assignments for the given matrix were examined. Amberlite IRA 400Cl is a strongly basic gel-type resin. It is a polystyrene divinylbenzene copolymer containing quaternary ammonium functional group. The most characteristic band of the spectrum is positioned to the left in range of 3,200-3,600 cm^{-1} due to the stretch of N-H bond. It appears as a broad band but not as broad as the O-H band in case of alcohols. Bands observed in the region of 1,550-1,640 cm^{-1} are due to N-H bends which are stronger in amides than amines. The polymeric matrix of styrene exhibits a spectrum band at 2,922 cm^{-1} due to the stretching of C-H group, whereas the band at 1,637 cm^{-1} is attributed to vibration of benzene ring [41,42]. On comparing the spectrum of gold loaded resin with fresh resin, the relative peak intensities observed at 3,438, 2,375 and 2,080 cm^{-1} region were found to differ from each other due the formation of metal complex between gold ions and quaternary ammonium group of the resin.

3-9. Studies for Elution of Gold

Studies for eluting gold from loaded Amberlite IRA 400Cl were performed using different concentrations of hydrochloric acid and thiourea [5% HCl+50 g/L SC(NH$_2$)$_2$ and 5% HCl+100 g/L SC(NH$_2$)$_2$] at A/R ratio 25 mL/g in contact time of 30 min. About 99.99% gold was eluted using 5% HCl+50 g/L SC(NH$_2$)$_2$ in four cycles, whereas three cycles were required for elution using 5% HCl+100 g/L SC(NH$_2$)$_2$ as shown in Fig. 11. Keeping in view the minimum consumption of chemicals, the mixture of 5% HCl+50 g/L SC(NH$_2$)$_2$
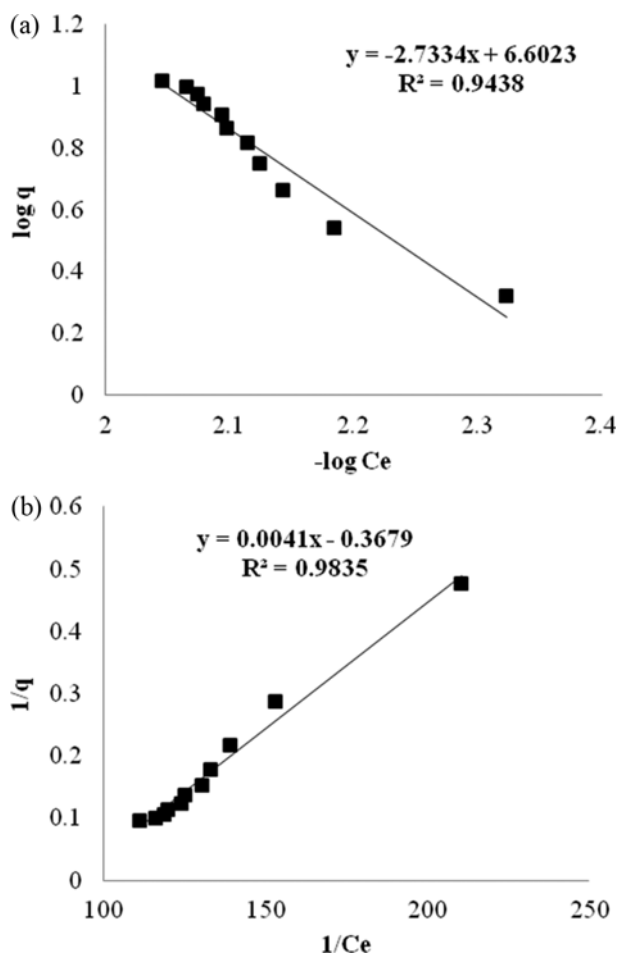

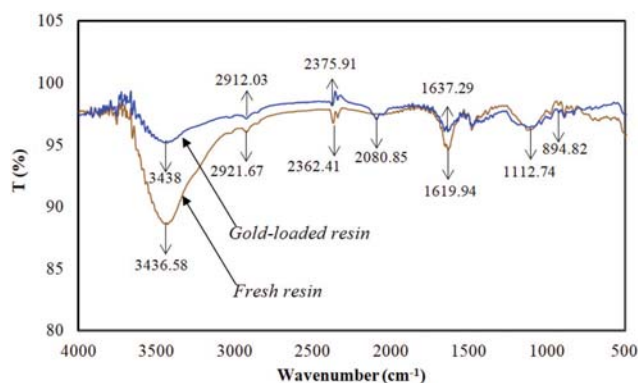Fig. 9. (a) Freundlich isotherm for adsorption of gold, (b) Langmuir isotherm for adsorption of gold.

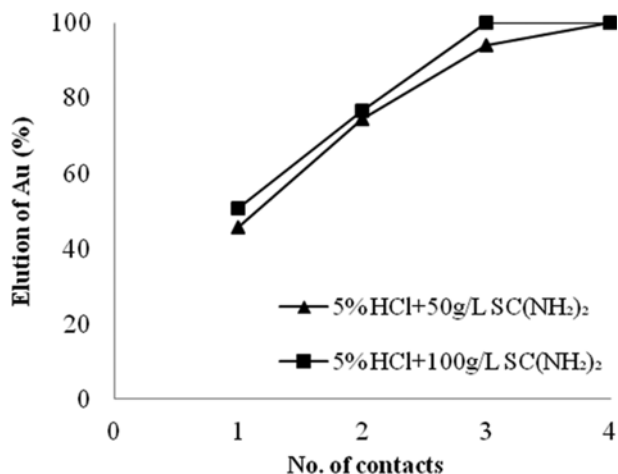Fig. 10. FTIR spectra of Amberlite IRA 400Cl resin.

Fig. 11. Elution of gold from loaded resin.

was considered suitable for elution of gold from loaded resin.

3-10. Column Studies

Column study for the adsorption of gold was carried out in continuous mode to validate the results obtained from batch experiments. Several sets of experiments were carried out and found that in batch experiments more surface area was available for gold adsorption due to proper shaking; however, to validate in column to maintain the same experimental condition the A/R condition and high concentration of eluent was used. 40 g of Amberlite IRA 400Cl was packed in a column and 5 L of raffinate containing 10 mg/L Au was passed through it. About 95.8% (~47.9 mg) Au got adsorbed onto the resin in three stages. Elution of the gold from loaded resin was attained using a mixture of 50% HCl and 500 g/L thiourea. Gold concentration in the eluate was found to be 882.41 mg/L, which is ~88 times more in comparison to the original raffinate used for experimental purpose. The obtained enriched solution of gold could further be processed using cementation/evaporation technique to recover gold as metal/salt.

Scale up studies for gold adsorption were also carried out using 15 L raffinate in continuous mode under optimized experimental condition. The raffinate was charged into the column containing 120 g of resin. About ~144 mg of gold from the raffinate got adsorbed onto the resin. On elution under similar experimental condition, purified solution of gold was obtained. The waste water left after ion exchange of gold was sent to effluent treatment plant for further treatment using standard procedure.

FOCUS ON ENVIRONMENTAL FRIENDLY PROCESS

Apart from containing precious metals, e-waste is also considered a perilous solid waste due to the presence of toxic metals: lead, mercury, cadmium, halogenated flame retardants, etc. [43,44]. The presence of such lethal substances causes environmental pollution, affects human health, and if gets leached into the soil, due to land filling, then it may also have an effect on the ground and surface water as well as aquatic life [45,46]. Therefore, safe disposal of e-waste has also emerged as a critical subject of interest in area of solid waste management [47]. Keeping in view the hazardous effects

of e-waste, different safety measures were followed for the treatment of leached residues, effluents and gases generated during the experiment prior to their disposal to the environment. The plastic materials left after gold leaching were treated using pyrolysis to collect organohalogens like polybrominated biphenyls (PBBs) and brominated flame retardants (BFRs) as low density oil [48,49]. Toxicity characteristic leaching procedure (TCLP) test was carried out for the residue left after leaching of metal, before its utilization or disposal to the environment. As leaching experiments were performed in closed reactor fitted with a condenser, therefore any gaseous emission during the experiments generated was condensed back, whereas the generated raffinate was recycled and reused in the system. The effluent generated after ion exchange studies was collected and sent to effluent treatment plant for neutralization before final disposal.

CONCLUSIONS

Based on the results obtained from the hydrometallurgical processing of discarded small components of electronic devices to recover gold, the following conclusions could be drawn:

• Small components of electronic devices like outer layer of PCBs and ICs are rich in precious metals (majorly gold).

• Recovery of gold from such secondaries is best achieved using hydrometallurgical route due to its selectivity, less consumption of energy and high purity product even from dilute solution.

• More than 95% gold was leached out from the discarded small components using 10 g/L cyanide in contact time of 15 min at 40 °C.

• Charcoal adsorption followed by burning at high temperature resulted in the recovery of gold metal with high purity.

• The raffinate generated after gold recovery was also a potential secondary source of gold containing ~10 mg/L gold. Ion-exchange technique proved to be fruitful in the recovery of gold from such dilute solution using Amberlite IRA 400Cl in 30 min maintaining A/R ratio 25 mL/g at eq. pH 9.6.

• Effective elution of gold was achieved from the loaded resin using a mixture of 5% HCl+50 g/L SC(NH$_2$)$_2$ in contact time of 30 min. The eluate obtained was found to contain about 88-times more concentration of gold compared to the actual raffinate.

• From enriched solution obtained, gold could be recovered as metal/salt by cementation/evaporation. The developed process flowsheet for the recovery of gold form small components of e-waste is presented in Fig. 12.

The process is viable and eco-friendly at laboratory scale and has potential for commercial exploitation after closed loop simulation of processes in continuous mode on pilot scale. The filtrate left after gold extraction and regenerated resin will be reused in the system, whereas the leached residues and effluents produced during the experiment will be properly treated using standard procedure before their final disposal to the environment. Total recycling of will not only minimize loss of precious metals but will also help in establishing organized sector for e-waste recycling, considering the environmental regulations as well as bring awareness among people related the loss of valuables due to dumping of such wastes into the environment.
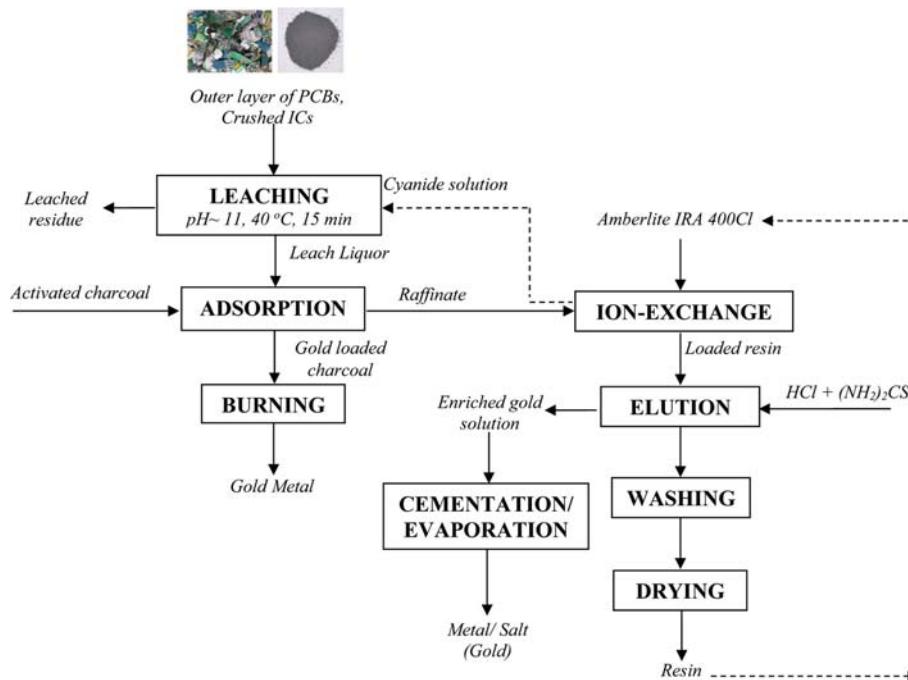
Fig. 12. Process flow-sheet for recovery of gold from small components of electronic waste.

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