

Article

Selective Gold and Palladium Adsorption from Standard Aqueous Solutions

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Abstract: The intensive exploitation of resources on a global level has led to a progressive depletion of mineral reserves, which were proved to be insufficient to meet the high demand for high-technological devices. On the other hand, the continuous production of Waste from Electrical and Electronic Equipment (WEEE) is causing serious environmental problems, due to the complex composition of WEEE, which makes the recycling and reuse particularly challenging. The average metal content of WEEE is estimated to be around 30% and varies depending on the manufacturing period and brand of production. It contains base metals and precious metals, such as gold and palladium. The remaining 70% of WEEEs is composed of plastics, resins, and glassy materials. The recovery of metals from WEEEs is characterized by two main processes well represented by the literature: Pyrometallurgy and hydrometallurgy. Both of them require the pre-treatment of WEEEs, such as dismantling and magnetic separation of plastics. In this work, the selective adsorption of precious metals has been attempted, using copper, gold, and palladium aqueous solutions and mixtures of them. A screening on different adsorbent materials such as granular activated carbons and polymers, either as pellets or foams, has been performed. Among these, PolyEther Block Amide (PEBA) was elected as the most performing adsorbent in terms of gold selectivity over copper. Spent PEBA has been then characterized using scanning electron microscope, coupled with energy dispersive spectroscopy, demonstrating the predominant presence of gold in most analyzed sites, either in the pellet or foam form.

Keywords: leaching; extraction; platinum group metals; precious metals; hydrometallurgy; adsorption



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1. Introduction

The diffusion of technology has significantly improved human life, giving day by day the innovations necessary to facilitate communications, transfer data, treat and defeat illnesses, and improve the quality of life [1]. However, these possibilities were accompanied by an increased consumables demand, but also by a significant increase of pollution and accumulation of waste. In particular, the continuous improvement of mobile phones, personal computers, and Internet Of Things (IOT), convinced and, in a certain manner, obliged people to substitute their devices very frequently [2]. This caused the parallel accumulation of Waste Electrical and Electronic Equipment (WEEE), divided into five large categories: (i) Mobile phones, printers, and computers, (ii) refrigerators and air conditioning systems, (iii) washing machines and dishwashers, (iv) monitors and TV, (v) and fluorescent lamps [3].

Precious Metals (PM) such as gold, palladium, and silver are important components for building electrical devices. Nowadays, this market is characterized by a continuous expansion [4]. According to data obtained from the United Nations (UN), 14 million tons of WEEE were generated in 1992, increased to 24 million tons in 2002, and more than tripled to 47.7 million tons in 2016 [5]. Today, the treatment of WEEEs represents a worldwide social problem, especially in some countries, where regulation enforcing waste

treatment is insufficient or unavailable. Currently, every year, more than 50 million tons of WEEE are discharged in the world. This phenomenon is particularly diffused in the poorest regions of the earth, where the methods of precious metals extraction lack sufficient safety rules for the operators [6]. Moreover, due to the pandemic situation, the transport of precious metals was reduced, while the condition of smart working was significantly increased. These two conditions resulted in a high request of microchips [7] and, therefore, of precious metals.

The treatment of WEEE is also characterized by a technological problem, due to the different historic periods of fabrication, the brand of production, and the type of electronic equipment produced. For example, the amount of precious metals used for the fabrication of computers in the eighties was much higher than the amount utilized nowadays [8]. Moreover, different brands of production resulted in different precious metals composition. Last but not less important, each electrical equipment has a different average metal composition [9–11].

For these reasons, researchers developed different methods to extract PM, with the aim to reutilize these materials by reintroducing them into the production route [12]. However, it is not easy to separate precious metals from waste devices. Indeed, pyrometallurgy requires high energy consumption, while hydrometallurgy applied on WEEE needs specific operating parameters in order to be selective [13–15]. An example is given by the Printed Circuit Boards (PCB), which contain up to 60 different metals simultaneously [16], including base metals, copper layers, precious and rare earths metals [17]. Therefore, the selectivity of this process applied to WEEEs is not always high [18]. Indeed, during leaching, not only precious metals, but huge amounts of Cu and base metals are extracted, as well [19]. At least 10% *w/w* copper is generally present in PCBs, while not more than 100 ppm (i.e., mg/L) of gold is content [20]. Therefore, refining of the leaching solution is required. This can be performed using different processing solutions, among these, selective adsorption represents a possibility [21]. This process is aimed at the recovery of precious metals such as gold and palladium from complex aqueous solutions and mixtures of these metal ions.

Polymers in their bulk state or, better, their foamed counterparts are often used as adsorbent materials, whether toxic, polluting or precious [22–24]. Therefore, granular activated carbons and polymers in pellets or foams have been largely used due to their high adsorption capacity of organic compounds or metallic ions [25]. Among these, foams can be used as adsorbent materials, due to their high porosity and uptake capacity [26–28]. For example, one of the popular techniques for oil spill remediation is the so-called physical remediation, where polymers such as polyethylene, polysulfide or carbon nanotubes laden foams [29,30] have been utilized. In these cases, the foamed structure has proven to be advantageous, both due to the increased specific surface available for adsorption and for the possibility to favor the bubble retention phenomena and consequent pores creation in foams. In particular, the volumetric retention can be optimized to the specific nature of the materials to be collected by fine tuning the pore architecture in terms of pore dimensions and open/close features, coupled with the physico-chemical interaction mechanisms. In the recovery of metals from WEEE by physical processes, low efficiency and high energy consumption have been observed [31–33] and the need for improved efficiencies is stringent.

Concerning the aims of the work, this paper represents a preliminary study performed on aqueous solutions of model ions such as copper, gold, palladium, and mixtures of them, at fixed concentrations and using fixed masses of different adsorbent materials such as polymers, foams, and granular activated carbons. A screening on these materials has been performed. At the end, this study also elects the best performing adsorbent material in terms of gold adsorption capacity over the copper uptake capacity.

2. Materials and Methods

2.1. Materials

Concerning the bulk aqueous solutions used in this study, three aqueous solutions (copper, palladium, and gold) have been employed. Each of these are prepared starting from Atomic Absorption Spectroscopy (AAS) standards and are characterized by a metal concentration of 1000 mg/L, containing 5% HCl in distilled water, on mass basis. The three standard solutions were purchased from Sigma Aldrich, Milan, Italy. The adsorption experiments reported in this work were performed by diluting the AAS standard solutions in distilled water down to 50 mg/L.

Concerning the adsorbent materials that were put in contact with the previously described aqueous solutions, in this work, a screening on many different granular activated carbons and polymers has been performed.

The GCN 1240 (Norit, Amersfoort, The Netherlands) and the Aquacarb 207 EA (Sutcliff Speakman Ltd., Ashton-In-Makerfield, UK) which are commercial granular activated carbons produced from coconut shell or bituminous coal, respectively, are available as pellets grinded in the range 12×30 , 12×40 mesh and used for wastewater treatment. The RO 3515 (Norit, Amersfoort, The Netherlands) is a sulphur impregnated activated carbon pellet, and is used for gold recovery in mine drainage. RO 3515 is generally characterized by a superior gold loading capacity, higher hardness, and mean particle diameter among 1.5 and 2.0 mm. The Char of South African coal ("char" thereafter) in the form of 1–2 mm grains was used as a potentially low cost sorbent, as proposed in the past by Di Natale et al. [34,35]. Finally, an activated carbon produced from gasification of scrap tires naturally containing C-S groups [36], available in the form of 1–2 mm grains, has been studied. The properties of these activated carbons have been reported in the reference papers cited above [34–36], the activated carbons available on the market have a cost of about 1–2 €/kg when not impregnated, and around 3–10 €/kg when impregnated. These materials show significantly different properties, such as their affinity to ion metals or to organic matter. The range of porosity may change depending on the kind of method used for their production.

This screening study has also been extended to polymers used as adsorbent materials, either in pellet or foam types. Some polymers have been investigated only in their foam form, such as Polyethylene Terephthalate (PET), Polyethylene (PE), and Polyurethane (PU) (the pellet form of these polymers was not available). However, Polyether Block Amide (PEBA) and Polypropylene (PP) were studied in both forms. The choice of materials was also conditioned by their possible affinity with metals dissolved in the solution [37–44]. Moreover, for the foams, the main sizes of these materials are very variable, as they depend on the process utilized for the foaming. The cost of polymer is similar or lower than that of GAC (for example, around 1 €/kg for PE and PET; 3.5 €/kg PEBA in pellet form). The other polymers used in this work have an average price among 1 and 3 €/kg.

2.2. Adsorption Tests

Adsorption tests consisted of the separation of metallic ions from the aqueous solutions, by contacting them with the desired sorbent (granular activated carbon or polymers in foam or pellet forms). In detail, at time zero, a given volume ($V_L = 20$ mL) of the aqueous solutions (palladium, copper, gold, a binary or a ternary mixture of them) was contacted with a mass of 100 mg of adsorbent ($m_{ads} = 100$ mg). Therefore, the ratio among V_L and m_{ads} , i.e., the ratio among the total liquid volume and mass of the adsorbent material, has been set at the constant value of 0.2 L/g. Tests were carried out at room pressure (1 bar) and temperature (20 ± 2 °C). The experiments were conducted in a batch-mode manner, in a reactor, at the stirring rate of 200 rpm, while the adsorbent materials were fully submerged in the 20 mL volume, inside 40 mL glass vials. Since the attainment of adsorption equilibrium requires a long time, the residual concentration of metal in the solution was monitored weekly (at 7, 14 and 22 days from the beginning of the experiment). Each experiment required three runs of measurement, using AAS spectrophotometer (SpectrAA

220, Varian; this instrument brand has been incorporated by Agilent Technologies, Santa Clara, CA, USA), and requires withdrawing 1 mL of the liquid sample. The actual volume representing the adsorption conditions were 20 mL after 7 days, 19 after 14 days, and 18 after 22 days. Adsorption tests were performed in triplicates.

In order to demonstrate the gold selectivity over copper of the adsorbent materials used, in the final part of this work, mixtures of the starting diluted aqueous solutions were prepared. In detail, binary mixtures (gold + copper, palladium + copper) and ternary mixtures (gold + palladium + copper) were prepared, with a total metallic concentration of 50 mg/L and total volume of 20 mL.

The adsorption uptake capacity of the metal $\omega_{A,i}$ was determined using Equation (1), as follows:

$$\omega_{A,i} = (C_{In,i} - C_{Res,i}) V_L / m_{ads} \quad (1)$$

where $C_{Res,i}$ is the residual concentration of the i -th metal ion, dissolved in the aqueous solution, during the adsorption process, and $C_{In,i}$ is the concentration of the metal ion in the starting aqueous solution.

2.3. Microscopy and Energy Dispersive Spectroscopy Characterization

The exhaust sorbents were further analyzed using SEM-EDS methods. After adsorption observations, the sorbents were extracted from the vial sample and dried under a vacuum. Then, a stub was prepared with these materials before Field Emission Scanning Electron Microscope (FE-SEM) and Energy Dispersive Spectroscopy (EDS) characterizations. The FE-SEM was a Merlin VP Compact (Zeiss, Oberkochen, Germany), coupled with a camera Gemini II and equipped with an inlens detector of backscattered and secondary electrons, a classic secondary electron detector, a BSE detector, and a variable pressure secondary electron detector. Moreover, it is connected to an Energy Dispersive microanalysis with an X-Max 50 detector (Oxford Instruments NanoAnalysis, High Wycombe, UK), and also to the WDS Wave spectrometer (Oxford instruments NanoAnalysis, High Wycombe, UK), characterized by four crystal analyzers for the EDS analysis.

The combination of EDS and WDS gives the possibility to analyze qualitatively and quantitatively the elements present on a sample spot of the SEM image. Dedicated software (Integrated Calibration and Application Tool (INCA), Etas Group, Stuttgart, Germany) allow obtaining distribution maps of the basic elements for the automatic acquisition of the mineralogical composition of the sample. The qualitative information concerning the peaks defines the presence of the specific element on the sample spot. Moreover, the quantitative information obtained is related to the mass percentage of the elements in that precise point chosen sample spot.

3. Results

3.1. Adsorption Experiments

The first performed adsorption experiments presented in Figure 1 show the adsorption capacity of the polymeric pellets, foams, and granular activated carbons for a 50 mg/L copper concentration. The residual copper concentration was measured after 7 days and, then, after 14 and 22 days.

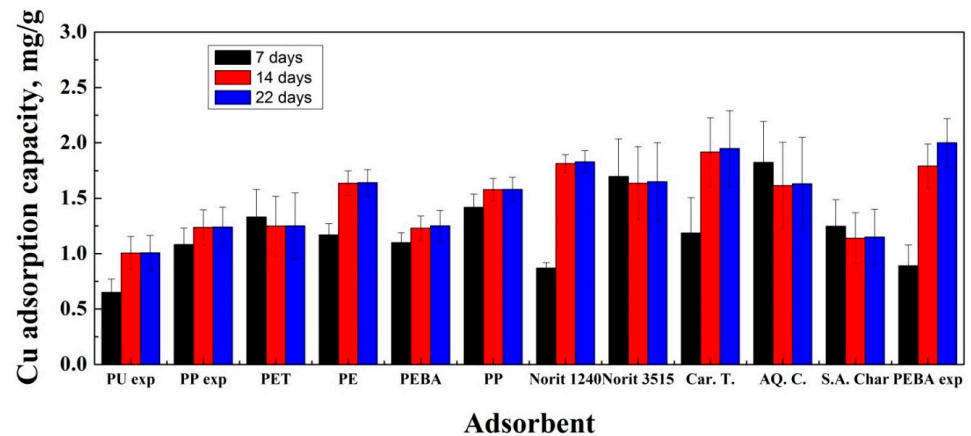


Figure 1. Copper adsorption capacities of different materials as a function of the test.

Figure 1 shows that, after the first 7 days of observation, the active carbon Aquacarb (AQ.C.) has reached an adsorption capacity of about 1.8 mg/g, while regarding Norit GCN 1240, it was below 1 mg/g. The foams such as PU, PP, and PET showed a discrete but not optimal adsorption capacity, ranging between 1 and 1.3 mg/g, while PE reached almost 1.5 mg/g adsorption uptake.

After 14 days, for some adsorbent materials, the adsorption capacity remained essentially the same, which means that the equilibrium has been reached within 7 days. This observation is regarding the PET and PP foams, Norit RO 3515, and S.A. Char. In other cases, the materials did not reach the equilibrium. This was not only the case for PU, PE, and PEBA foams, but also for Norit 1240 and Car.T. In particular, PEBA foam and Norit 1240 almost doubled their adsorption capacity from 7 to 14 days. After 22 days of observation, it could be possible to say that negligible alterations of the adsorption capacity have been observed and all the materials reached equilibrium concentrations.

The same screening operation was repeated using the palladium aqueous solutions. Results are reported in the bar diagram of Figure 2.

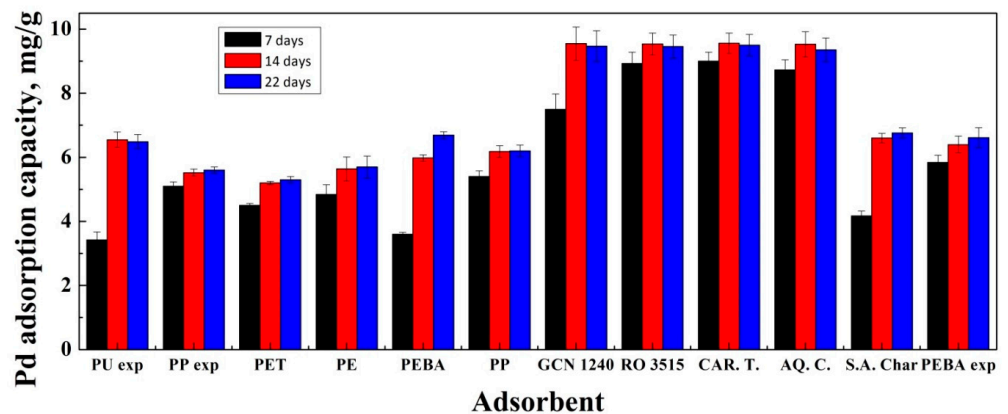


Figure 2. Palladium adsorption capacities of different materials as a function of test time.

From this study, it appears quite evident that some of the activated carbons needed only 7 days to reach equilibrium conditions, which is particularly evident for Norit RO 3515, Car.T., and AQ.C., while Norit GCN 1240 still needed some additional time to reach the equilibrium. The same behavior was registered for S.A. Char, which showed a Pd adsorption capacity of 4 mg/g at 7 days that became almost 6 mg/g after 14 days.

The pellet and foam polymers showed a variable behavior: PU, PP, PET, PE, and PEBA foams reached the equilibrium within 14 days. In particular, the expanded PU reached 6.5 mg/g adsorption capacity after 14 days, while the expanded PP, PET, and PE about 6 mg/g. PEBA in pellet and PEBA foam reached an adsorption equilibrium at

almost 7 mg/g, while active carbons reached a value of 10 mg/g. For the adsorption of palladium, it seemed a good choice to use activated carbons, independently from their different properties or porosities.

Tests on gold adsorption are reported in Figure 3.

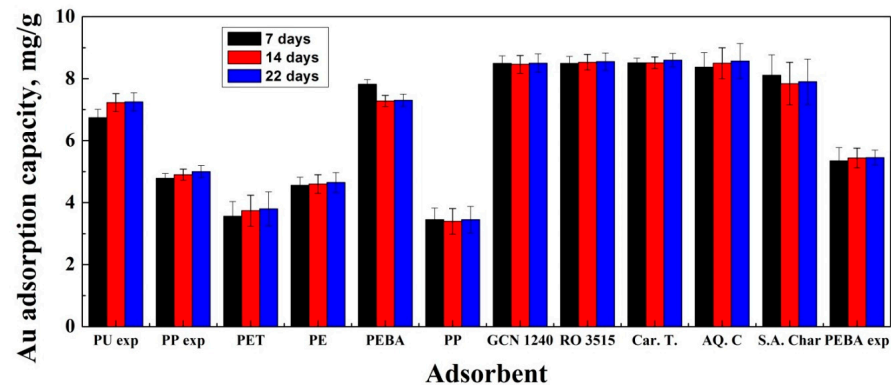


Figure 3. Gold adsorption capacities of different materials as a function of test time.

As indicated in Figure 3, activated carbons reached the equilibrium concentration within 7 days. Indeed, Norit GCN 1240, Norit RO 3515, AQ.C., CAR.T., and S.A. Char showed an uptake capacity of about 8 mg/g after 7 days.

In the case of gold adsorption, polymers showed a different behavior: They reached the equilibrium condition during the first observation time. However, their equilibrium values were lower than those of granular activated carbons: They ranged between 4 and 5 mg/g for PP, PET, PEBA, and PE foams, and also for PP in pellet. Instead, they were about 7 mg/g for PU foam and PEBA in pellet. Indeed, PEBA pellets showed a gold adsorption uptake similar to the one obtained using granular activated carbons.

Each adsorbent material has been characterized singularly, in terms of their copper, gold or palladium uptake capacity. However, one of the main problems of precious metals recovery is the need to separate precious metals from a mixture of precious and non-precious metals. For this reason, each adsorbent material has been studied in terms of gold over the copper uptake capacity ratio, and in terms of palladium over the copper uptake capacity ratio.

This first experimental campaign, whose results are shown in Figures 4 and 5, was useful to identify the best adsorbent material in terms of gold over copper and palladium over copper selectivity, assuming that gold and palladium are precious metals and the copper simulates as a model of non-precious metal, according to gold, palladium, and copper actual market values.

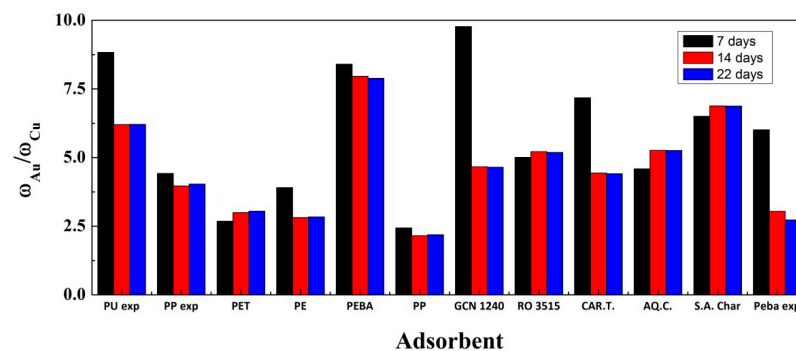


Figure 4. Gold/copper adsorption capacities of different materials as a function of test time.

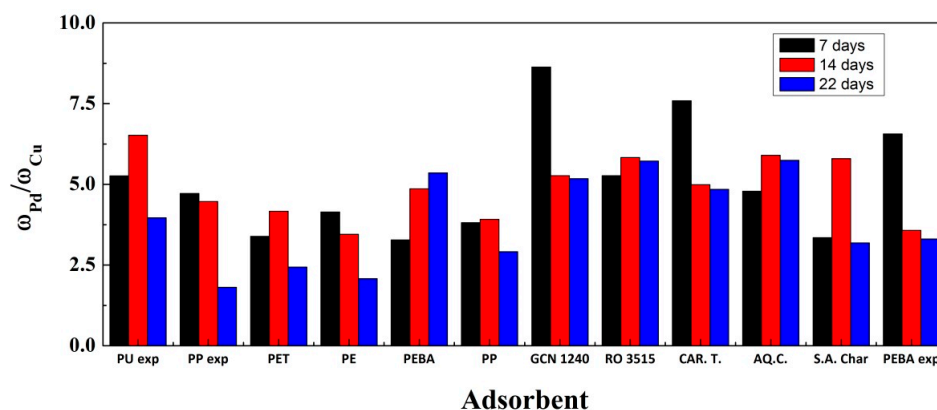


Figure 5. Palladium/copper adsorption capacities of different materials as a function of test time.

As shown in Figure 4, for some materials the adsorption uptake of gold is at least 2.5 times more efficient than copper adsorption uptake. This is shown by PET, PE, and PEBA foams, and almost by PP in pellets. The PU foam, after reaching the equilibrium condition, showed gold adsorption uptake 6 times larger than copper adsorption. Granular activated carbons showed a 5 times larger adsorption uptake of gold over copper. It is also worth noting that some materials have a faster adsorption uptake of gold (black bars at 7 days), and a simultaneous slower adsorption of copper. Indeed, in the first 7 days, this is particularly evident for PU foam, Norit GCN 1240, and Car.T. Then, these ratios decrease at 14 (red bars) and 22 days (blue bars), when the adsorption uptake of copper becomes faster: Adsorption time can be a way to improve selectivity.

Among all the materials studied as sorbents, PEBA in pellets has the largest ratio of gold over copper uptake, equal to almost 7.5, and constant from 7 to 22 days of observation. These results describe that PEBA could be indicated as the most promising adsorbent material in terms of gold selective adsorption, among the ones explored.

In Figure 5, the ratios of palladium over copper adsorption uptakes have been reported. Moreover, in this case, almost all the granular activated carbons showed an equilibrium adsorption uptake ratio (at 22 days) of about 5, except for S.A. Char, that was first characterized by a faster palladium uptake (7 days), then by a faster copper uptake (from 7 to 14 days), and finally, again, a faster palladium uptake (from 14 to 22 days). PEBA pellets showed, in this case, a similar ratio to granular activated carbons, as well as PU foam. Other foams only reached a 2.5 ratio among palladium and copper adsorption uptake. PEBA foam also showed a very fast palladium uptake at 7 days (more than 6 times over copper), followed by a significant copper uptake (within 7 and 22 days), corresponding to a ratio of almost 3.

The experimental results of Figures 4 and 5 indicated that PEBA is the material showing the highest selectivity in terms of palladium or gold adsorption, with respect to copper. This polymer has the ability to adsorb a reduced amount of copper (less than 1.5 mg/g for PEBA in pellet and less than 2 mg/g for PEBA foam), while it is highly selective in terms of gold uptake capacity (8 mg/g for PEBA pellet and 5.5 mg/g for PEBA foam). The palladium uptake capacity was instead almost 6 mg/g for both forms of PEBA. This means that PEBA is potentially able to separate non-precious metals and copper (that has a lower market value) from other precious metals, with an acceptable selectivity.

In Figure 6a, the ratios Au/Cu and Pd/Cu adsorption uptakes, after 22 days, were selected and further compared. In Figure 6b, macroscopic observations of PEBA pellets, treated with a gold aqueous solution, has been shown as a qualitative demonstration of gold adsorption on the material, clarifying the aqueous bulk solution.

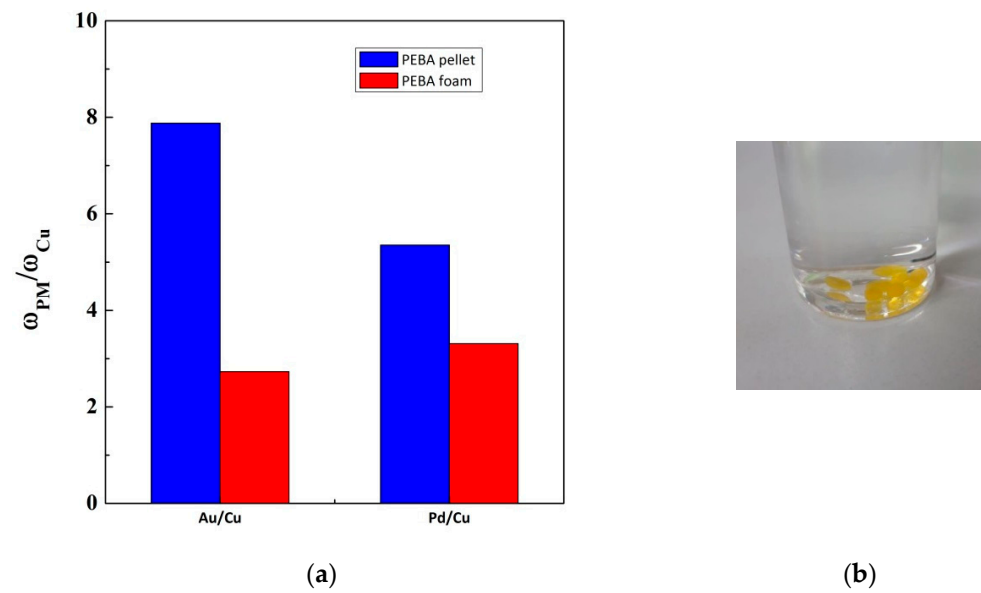


Figure 6. Palladium and gold over copper adsorption capacities after 22 days of PEBA polymer (a), followed by a macroscopic example image of gold adsorbed on PEBA (b).

3.2. SEM-EDS Characterizations

SEM-EDS observations have been performed on PEBA pellet and foam, due to their higher gold and palladium selectivity. Figure 7a reported SEM observations of clear native PEBA pellet. On the surface of the pellet, some points were identified and analyzed using EDS, all the obtained spectra revealed the presence of carbon, silicon, and chloride in the main structure. As an example, one of the spectra obtained for each analyzed site is reported on the right of its SEM image. Figure 7b represents the EDS spectrum of native, clear, PEBA pellet, useful as a comparison with the following samples.

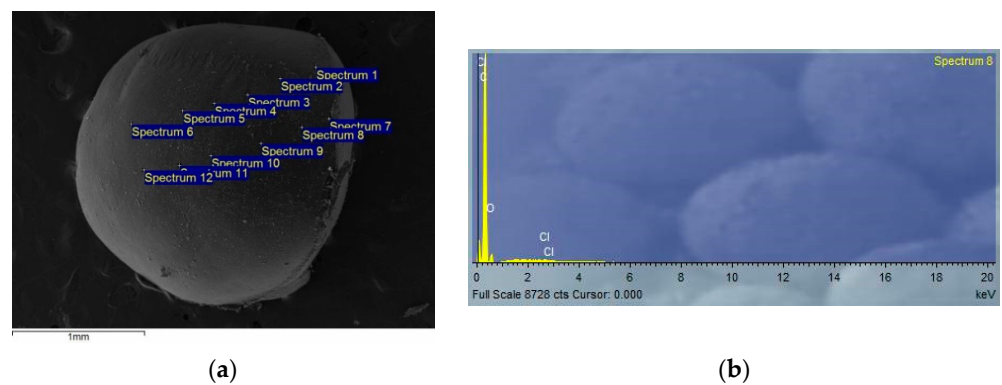


Figure 7. Cont.

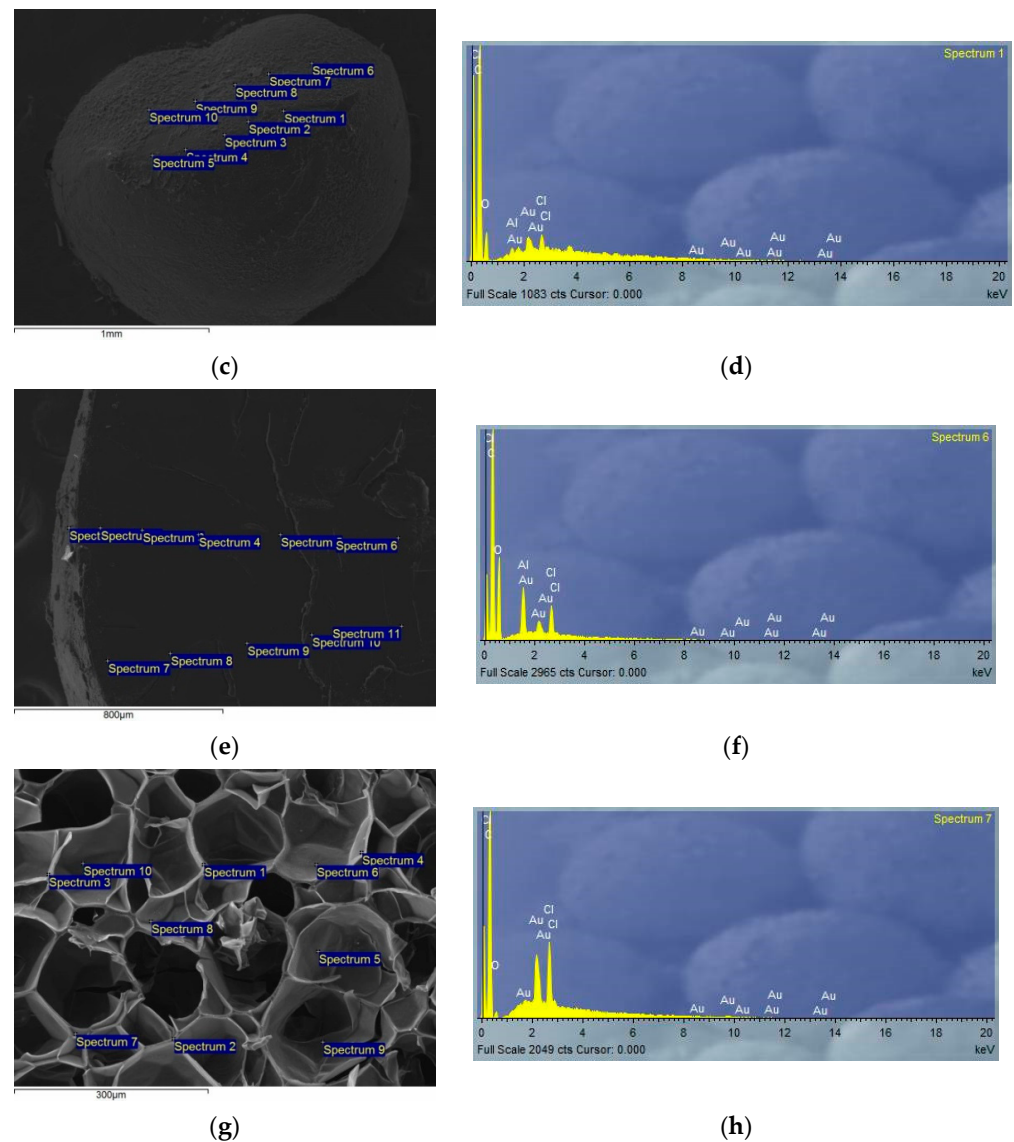


Figure 7. (a,b) Represent the SEM and the EDS spectrum obtained on a native PEBA pellet, respectively; (c,d) represent a SEM image of the PEBA pellet surface, and the EDS spectrum of the elements found on it; (e,f) represent the SEM + EDS analysis performed on the PEBA pellet section; (g,h) represent the SEM and EDS analysis obtained from the PEBA foam.

Once observed, the main constituent elements of PEBA granules, the SEM+EDS observations on the dried external surface of PEBA pellet (Figure 7c,d), dried pellet section (Figure 7e,f) and dried PEBA foam section (Figure 7g,h) were performed, after being in contact with the gold aqueous solution.

The knowledge obtained from the SEM+EDS measurements (see Materials and Methods Section) gave a description of the species found on the surface and the section of PEBA pellets and foams. In the following Figure 7, we selected several spots on the SEM images, whose most representative EDS spectra have been obtained.

Figure 7d,f clearly shows the presence of gold over the surface and inside the PEBA pellets, demonstrating that the diffusions of gold ions managed to reach the center of the polymer pellet. Figure 7h, referring to the case of PEBA foam, indicated the presence of gold in the holes inside the foam, showing that gold penetrated deeply in the structure of the PEBA foam.

These results were also coupled and integrated with further information given in Table 1, where the metal content was quantified for PEBA pellet and foams, as a mass

percentage related to the total mass identified in each chosen point spot of the SEM image. Random spots were chosen from the region (surface or section of the pellet and foam) of the adsorbent analyzed. Gold, palladium, and copper percentages are reported as minimum-maximum of the amount identified among the points chosen in each SEM image analyzed.

Table 1. EDS characterizations of PEBA pellet and foam.

Ads. Type	Ads. Region	Au, <i>w/w</i> %	Pd, <i>w/w</i> %	Cu, <i>w/w</i> %
PEBA	Surface	0.25–3.79	0–0.06	0–0.04
	Section	0.26–0.90	0–0.12	0–0.03
PEBA foam	Surface	0.53–7.35	0–0.10	0–0.16
	Section	0.77–2.76	0–0.21	0–0.17

As indicated in Table 1, the investigated sites (reported in the SEM images) of the surface and section of dried PEBA were characterized by a range among 0% and a maximum of 0.17% *w/w* copper. The same behavior was registered on foams and active carbon sites (data not reported). The maximum detection value for palladium was found to be among 0.06% (on the surface of pellet) and 0.21% *w/w* (section of foam). In the section of PEBA in pellet, the investigated sites contained from 0.26 to 0.90% *w/w* gold. On the surface of PEBA pellet, it was among 0.25 and 3.79% *w/w*. Concerning the PEBA foam, the external slices contained from 0.53 to 7.35% *w/w* gold, while in the inner slices, gold content was among 0.77 and 2.76% *w/w*. The authors believe that the differences among the first observed adsorption experiments and the EDS analysis are due to the washing and drying of the samples, which were performed before the SEM observations. As shown, the presence of a penetration gradient was not demonstrated.

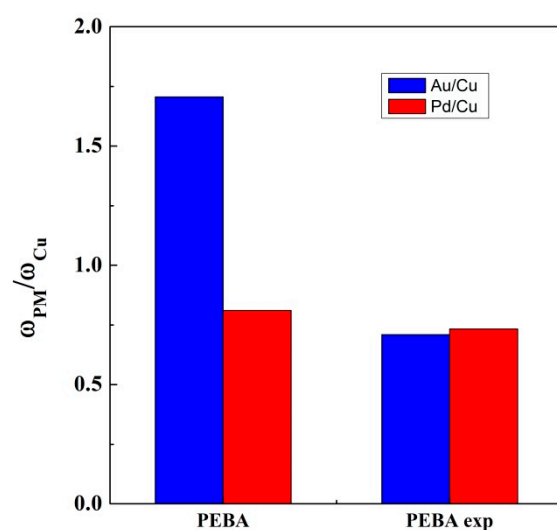
Even if the quantification of gold on the surface of PEBA foams reached higher maximum values, gold ions distribution appeared not particularly homogeneous, probably due to the presence of preferential points and/or surface defects. Maybe this could be also due to the preparation of the samples for SEM + EDS characterization. Instead, the PEBA pellet shows a more flat distribution.

In order to evaluate possible interactions among the different metals, in the final part of this study standard aqueous solutions were mixed together to simulate real leaching situations with two or three metallic ions dissolved simultaneously in the same solution. In particular, PEBA in pellet and foams was put in contact with Au + Cu solutions, Pd + Cu solutions, and Au + Pd + Cu solutions. The total volume of these new solutions was kept constant at 20 mL, as well as metal starting concentrations (50 mg/L). In the two-metal solutions, the repartition was 50/50% on mass basis, regarding the three-metal solutions, the repartition was 33.3/33.3/33.3% on mass basis.

In Table 2, the results in terms of $\omega(\text{Au})/\omega(\text{Cu})$ and $\omega(\text{Pd})/\omega(\text{Cu})$ in the binary solutions and ternary aqueous solutions were reported for PEBA foam and pellets, while in Figure 8, a comparison on adsorption capacity has been focused on the ternary aqueous solutions for the same adsorbent materials.

Table 2. Au, Pd, and Cu adsorption uptake in mixed aqueous solutions.

Ads. Type	Mixture of Aqueous Solutions	ω (Au)	ω (Pd)	ω (Cu)	ω (Au)/ ω (Cu)	ω (Pd)/ ω (Cu)
PEBA pellet	Au + Cu	3.288	—	2.776	1.184	—
	Au + Cu + Pd	2.677	1.272	1.569	1.706	0.811
	Pd + Cu	—	1.439	2.203	—	0.653
PEBA foam	Pd + Cu	—	2.422	2.989	—	0.810
	Au + Cu	2.976	—	2.819	1.056	—
	Au + Cu + Pd	1.013	1.047	1.428	0.709	0.733

**Figure 8.** Au/Cu and Pd/Cu adsorption capacity using ternary mixtures of the aqueous solutions.

As shown from Table 2 and Figure 8, PEBA pellets have the highest gold over copper selectivity (1.75 adsorption uptake ratio, Au/Cu). The amount of adsorbed palladium is instead comparable with the copper amount. PEBA foam showed a similar behavior in terms of gold and palladium selectivity. These values are different from those derived from the comparison of mono-component solutions (Figure 6) and suggests the need for further studies on multi-component mixtures.

4. Conclusions

In this work, we studied the behavior of several materials as adsorbers for gold, palladium, and copper ions from aqueous solutions. Granular activated carbons, polymers in pellet and foams were studied in terms of gold/copper and palladium/copper adsorption capacity.

This preliminary screening allowed identifying PEBA as the best performing material in terms of gold selectivity. Polyether block amide was studied in its pellet and foam form with further SEM+EDS characterizations. Gold ions were found on surface and inner sections, in either foams and pellets of PEBA. However, the distribution of gold ions adsorbed on these materials were much more homogeneous when working with PEBA in pellet, than foam.

In general, adsorption of metal ions in the solution mostly depends on chemical interactions between the specific ion form and functional groups over the adsorbent surface. In activated carbon, there are a number of different functional groups and previous studies on other soft-ions as palladium, lead or mercury, whose behavior is expected to be similar to that of gold and platinum [35,45–47], suggesting that adsorption should involve reducing C-O groups, as phenols and lactones, C-S or C-N groups, as well as aromatic rings. The mechanisms of adsorption on foams are likely to include similar interactions

with C-O functionalities and aromatic rings, but the adsorption on PP and PE suggests interactions with simple C-C or methyl groups. Further efforts are needed to define the actual mechanism of adsorption over the polymer foams.

The preference for PEBA in pellet was confirmed by the results obtained on binary and ternary mixtures of metallic aqueous solutions, which showed almost 1.75 times larger selectivity of gold with respect to copper adsorption capacity. These preliminary results suggest that PEBA pellets deserve further investigation as an adsorbent to recover selectively gold and other precious metals from WEEE leachate solutions.

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Abbreviations

WEEE: Waste Electrical and Electronic Equipment; PE: Polyethylene; PP: Polypropylene; PET: Polyethylene Terephthalate; PU: Polyurethane; PEBA: Polyether Block Amide; m_{ads} : Mass of the Adsorbent; A.Q.C.: Aquacarb; Car.T.: Carbon from Tires; EDS: Energy Dispersive Spectroscopy; FE-SEM: Field Emission Scanning Electron Microscope; PGM: Platinum Group Metals.

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