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SUSTAINABLE RECOVERY OF PRECIOUS METALS FROM CHLORIDE SOLUTIONS BY SOLVENT EXTRACTION

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Abstract: Solvent extraction in hydrometallurgical processing is a suitable method for precious metals extraction/separation from chloride solutions and therefore proven to be an alternative to the conventional method of separation. This paper presents results of the removal of palladium(II), gold(III) and platinum(IV) ions from chloride media in the extraction-stripping process using trihexyl(tetradecyl)-phosphonium tetrafluoroborate $[3C_6C_{14}P]BF_4$ as the extractant. The efficiency of extractive separation of the examined metals depends on the acidity of the aqueous solution. The stripping from a loaded organic phase provides effective and quality separation of palladium(II), gold(III) and platinum(IV). The extractant studied ($[3C_6C_{14}P]BF_4$) can be reused in the next cycles of the extraction-stripping-regeneration process without a significant loss in the extraction power, which is in line with the assumptions of sustainable recycling.

Keywords: precious metals recovery, solvent extraction, sustainable recycling, waste electronic and electrical equipment (WEEE).

1. INTRODUCTION

The demand for precious metals has been growing for several decades due to these metals have been for many years used as catalysts in the organic technology processes, as boosters in motor vehicle catalytic converter systems and recently as afterburners in modern, environmentally friendly domestic furnace installations. In 2024, the demand for palladium was 302.7 tonnes, platinum 236.8 tonnes, rhodium 33.1 tonnes and gold 4,974 tonnes, and their prices were $924/oz, $956/oz, $4,750/oz and $2,386/oz, respectively [Matthey 2024; Statista; World Gold Council 2024].

The rarity of palladium and platinum, which belong to the platinum group metals (PGMs), in the Earth's crust and their geographic concentration are a global concern, given the projected increase in demand for these metals. Global mineable PGM resources were estimated at 100 million kg in 2021. The increasing demand and rarity of platinum group elements increase the need to increase processing

efficiency and/or recycling efficiency to maintain supplies of these elements [Makvandi et al. 2021; MacDonald, Zhang and Karamalidis 2024].

The recovery of platinum group metals from primary ores is associated with challenges, including low platinum group metal content, high energy consumption, and limited recovery concentrations. Secondary resources, on the other hand, are characterised by significantly higher platinum group metal concentrations, making them highly preferable for exploitation while reducing the need for intensive ore mining. Secondary sources require significantly less energy, achieve higher recovery efficiencies, and have a lower environmental impact [Yakoumis et al. 2021; Michałek, Hessel and Wojnicki 2024]. Gold is not typically considered a critical metal. However, according to Trench et al. (2023) and others, major gold producers are aiming to achieve net-zero emissions by 2050, combined with a smaller overall environmental footprint, to meet growing societal demands for cleaner production as part of the clean energy transition. Because gold is mined in far more countries, including developing countries, than critical minerals, the gold industry is in a position where the energy transition will inevitably impact it, and gold mining companies are already embracing the clean energy transition. Providing renewable energy infrastructure to power gold mining and processing operations is therefore likely to accelerate the broader implementation of green energy solutions in remote regions where gold mines are located. Therefore, gold plays a unique, albeit indirect, role in facilitating the transition to net-zero emissions and is therefore sometimes included in the list of critical metals [Müller et al. 2025].

Electronic waste is a growing problem worldwide. Technological advances and increased automation in the industry have contributed to the increased use of electronic and electrical equipment. Electrical and electronic products have become commonplace in the everyday life of the average consumer and are also widely used in various industries. At the same time, the development of advanced, faster and more reliable computing and data processing technologies has led to a shortening of the product life cycle, forcing consumers to purchase newer and more up-to-date technologies while discarding older products. All these changes have led to a sharp increase in the amount of electronic waste generated. The amount of electronic and electrical equipment (EEE) placed on the market in the EU evolved from 7.6 million tonnes in 2012 to 14.4 million tonnes in 2022. Over the period 2012–2022 as a whole, the amount of EEE put on the market grew by 89.3%. The total collected WEEE increased from 3.0 million tonnes in 2012 to 5.0 million tonnes in 2022 (+67.9%), while the total treated WEEE grew from 3.1 to 4.9 million tonnes (+56.8%) over the same period. Recovered WEEE developed from 2.6 to 4.5 million tonnes (+72.1%), and WEEE recycled and prepared for reuse grew from 2.4 to 4.0 million tonnes (+66.6%) from 2012 to 2022 [Eurostat 2024].

WEEE contains about 60 different components, such as: noble metals (Au, Ag, Pd, Pt), basic and special metals (Cu, Al, Ni, Zn, Fe, Se, In, Ga), hazardous metals (Hg, Pb, Cd, Be, As), halides (Br, Cl), plastics, glass and ceramics [Heacock et al. 2016; Kumar, Holuszko and Espinosa 2017; Zulkernain et al. 2023].

The recovery of these metals through WEEE recycling can fill the gap between demand and very limited natural deposits. Recycling of electronic waste also contributes to reducing the amount of materials stored in landfills. However, with all the potential benefits of recycling, only 20% of global e-waste is fully processed [Eurostat 2024].

In accordance with Annex 1 to the Waste Electrical and Electronic Equipment Act of September 11, 2015, a six-group classification of electrical and electronic equipment has been in effect since January 1, 2018. This classification was introduced due to the specific collection and processing costs of waste devices within each group [Act of 11 September 2015, Journal of Laws 2022, item 1622]:

(1) temperature-changing devices: refrigerators, freezers, air conditioners, heat pumps;

(2) screens and monitors: televisions, monitors, laptops, notebooks, tablets;

(3) lamps: fluorescent lamps, LED lamps, high-intensity discharge lamps;

(4) large equipment: washing machines, clothes dryers, electric cookers, large printing machines, photocopiers, photovoltaic panels;

(5) small equipment: vacuum cleaners, toasters, microwave ovens, ventilation equipment, scales, calculators, radios, electric shavers, kettles, cameras, toys, electronic tools, medical devices, small monitoring and control devices;

(6) small IT and telecommunications equipment: mobile phones, pocket calculators, routers, GPS devices, personal computers, printers, telephones.

Each product in the six WEEE categories has a different 'lifespan', meaning that each category has different waste volumes, economic values, and potential environmental and health impacts if not properly managed or processed. Therefore, the collection and logistics processes and recycling technology differ for each category.

In addition, from 1 January 2021, the entity introducing the equipment is obliged to achieve minimum annual levels of waste equipment collection, which are no less than 65% of the average annual mass of equipment introduced to the market or 85% of the mass of waste equipment produced in the territory of the country [Act of 11 September 2015, Journal of Laws 2022, item 1622].

Considering the fact that waste electrical and electronic equipment is the fastest-growing waste stream in the world, its recycling makes perfect sense. Precious metals account for more than 70% of the value of mobile phones, calculators and printed circuit boards and 40% of TV and DVD discs [Zhang and Xu 2016; Holgersson et al. 2018]. Sustainable recycling is measured by assessing the recycling efficiency, environmental impact, and commitment to a circular economy. It is important to monitor the amount of materials recycled, reduction in raw material consumption, CO2 emissions reduction, and water conservation. Recycling of precious metals from e-waste reduces CO2 emissions because it uses less energy than recovering the same form from primary metal ores. It is estimated that for every tonne of gold recovered from natural mines, 17,000 tonnes of CO2 emissions are produced [Chauhan et al. 2018; Zulkernain et al. 2023]. Unfortunately, Europe is not

exploiting the potential of e-waste and is losing $10 billion worth of metals and 4 million tonnes of potential CO2 savings annually by not recovering metals from e-waste [Balde et al. 2024].

Processing 1 tonne of waste mobile phones can yield 0.2–0.35 kg of gold, while processing the same amount of ore yields approximately 0.05 kg of gold [Holgersson et al. 2018]. The content in g·t−1 of gold, silver, and palladium in printed circuit boards are 2.5, 100, and 11, respectively, while the gold content in the gold mines around the world ranges from 0.33 to 0.2 g·t−1 [Zulkernain et al. 2023; Balde et al. 2024]. Furthermore, recovering metals and other valuable elements from e-waste also creates business opportunities because it creates a new life cycle for electrical and electronic products. For example, several computer components can be reused to assemble computers for basic computing purposes in rural primary schools and offices, while the remaining materials can be used in various ways in construction, computer equipment, and jewellery [Luhar and Luhar 2019; Mudali et al. 2021; Kaliyavaradhan et al. 2022].

Currently, the recovery of precious metals from natural and spent materials is carried out using traditional pyrometallurgical or hydrometallurgical methods. Hydrometallurgical processing of waste materials has been the area of the most intensive research in the field of wet techniques for the last two decades. Solvent extraction in hydrometallurgical processing is one of the major industrial-scale refining processes of precious metal chlorocomplexes. This method has benefits for its suitability to treat solutions with high metal content, improved degree of extraction and separation yields, capability of continuous operation, recycling of the organic extractants, flexible and versatile process control, and fast kinetics. Therefore, reagents capable of extracting these metals have recently become a subject of interest for many researchers worldwide. Selecting an extractant that ensures maximum extraction efficiency requires consideration of a number of parameters, including the type of metal, acidity of the solution, and temperature. The most desirable characteristics of a perfect extractant include: the ability to make a permanent chemical bond with the extracted metals in reversible reactions; the ability to reach extraction equilibrium in a short time, i.e. to have a high rate of extraction; chemical stability; overall solubility of the active ingredient in the free form and bound to the metal; poor solubility in an aqueous phase; and the lack of a tendency to form a third intermediate stage [Bernardis, Grant and Sherrington 2005].

Until now, many types of extractants have been studied and proposed for the recovery and separation of precious metals, such as hydrophobic amines [Jha et al. 2014; Nguyen, Sonu and Lee 2016; Nguyen et al. 2021], organophosphorus extractants [Gupta and Singh 2013; Nguyen, Sonu and Lee 2015; Paiva et al. 2022], calixarenes [He et al. 2022], different derivatives of amides [Ortet and Paiva 2015; Mowafy and Mohamed 2016; Sasaki et al. 2017; Costa et al. 2018; Moussaoui et al. 2021; Song et al. 2022; Xiao et al. 2022], pyridine [Khogare et al. 2016a; Wiecka et al. 2023], and piperidine [Cieszyńska and Wieczorek 2018]. In the solvent extraction process, ionic liquids (ILs) have found prospects of being used as active extractants

(diluted or undiluted), diluents for both molecular extractants (MEs) and ILs, and task-specific ionic liquids (TSILs) [Kurniawan, Kim and Lee 2022]. ILs as active extractants have shown a capacity for high extraction and successful separation of complex metal ion systems, including precious metals chlorocomplexes, e.g. ammonium, phosphonium, imidazolium, pyridinium, piperidinium, pyrrolidinium and betainium ionic liquids [Wei et al. 2016; Firmansyah, Kubota and Goto 2018; Mohdee et al. 2018; Boudesocque et al. 2019; Rzelewska-Piekut and Regel-Rosocka 2019; Cieszyńska and Wieczorek 2020; Nguyen, Riano and Binnemans 2020; Lim et al. 2021; Rzelewska-Piekut, Paukszta and Regel-Rosocka 2021]. Most studies are focused on separating palladium(II), and gold(III), and platinum(IV). Successful separation of these three metals is often impossible by simple extraction. However, the use of the extraction-stripping process allows the separation of palladium(II) from gold(III) and platinum(IV).

It is the aim of the work to establish the abilities of the trihexyl (tetradecyl)phosphonium tetrafluoroborate – [3C6C14P]BF4 – to extract and separate palladium(II), gold(III) and platinum(IV) from hydrochloric acid solutions. The selectivity of palladium(II) stripping over gold(III) and platinum(IV) with different stripping solutions and the feasibility of regenerating [3C6C14P]BF4 and its reuse in subsequent extractions have also been investigated.

2. MATERIAL AND METHODS

2.1. Reagents

Commercial palladium chloride PdCl2 (99%, Avantor Performance Materials Poland S.A., Poland), platinum chloride PtCl4 (99%, Avantor Performance Materials Poland S.A., Poland), gold chloride AuCl3 (99%, Aldrich, Poland), hydrochloric acid (analytically pure, 35–38%, Chempur, Poland), nitric acid (analytically pure, 65%, Avantor Performance Materials Poland S.A., Poland), thiourea (analytically pure, Chempur, Poland) and aqueous ammonia (analytically pure, 25%, Chempur, Poland) were used to prepare aqueous solutions. Commercial pure trihexyl (tetradecyl)phosphonium tetrafluoroborate [3C6C14P]BF4 (pure, ≥95%, Sigma-Aldrich) was used as the extractant. Toluene (analytically pure, Chempur, Poland) was used as the diluent of the extractant.

2.2. Procedure

The aqueous feed contained 85 mg L^{-1} Pd(II), 200 mg L^{-1} Au(III) and 30 mg L^{-1} Pt(IV). The concentration of metals in model solutions was not equimolar, to simulate real conditions obtained after WEEE leaching [Firmansyah, Kubota and Goto 2024]. Stock solutions were prepared by dissolving appropriate amounts of their suitable chlorides in double distilled water containing a minimum amount of the corresponding mineral acid. The acidity of the solution was controlled by HCl

solution (from 0.1 to 3.0 M). The organic phases were 2.5 and 5 mmol · L^{-1} solutions of $[3C_6C_{14}P]BF_4$ in the presence of toluene.

Extraction was carried out in a typical way. Both phases were mechanically shaken in glass separatory funnels (volume ratio A/O = 1) for 10 minutes at room temperature (20±1°C). After mixing, both phases were left to stand and then separated. The loaded organic phase was stripped with 3.0 M HNO_3, 0.5 M aqueous ammonia or 0.1 M thiourea in 0.1 M HCl (A/O = 1). Microwave plasma-atomic emission spectroscopy (4210 MP AES, Agilent, USA) was used for metal determination in the initial aqueous solutions and in the aqueous phases after extraction and stripping.

Percentage extraction (E) was calculated from the concentration of metal ions in the aqueous phases before $[M]_{(i)}$ and after $[M]^*_{(aq)}$ extraction:

$$E = \frac{[M]_{(i)} - [M]^*_{(aq)}}{[M]_{(i)}} \cdot 100\%$$

The volumes of the phases did not change. Each experiment was carried out three times, and the error did not exceed 5%.

3. RESULTS AND DISCUSSION

Precious metals (PMs) in acidic chloride solutions form a series of complexes depending on the HCl concentration and oxidation states of the metals. Chlorocomplexes of palladium(II): $PdCl^+$, $PdCl_2$, $PdCl_3^-$ and $PdCl_4^{2-}$ co-exist in solutions with a lower concentration of chloride ions, while in chloride media of Cl^- concentrations of 0.1–5 mol L^{-1}, the predominant species of palladium(II) is $PdCl_4^{2-}$. Platinum (IV) forms the following complexes: $[Pt(OH)_6]^{2-}$ (pH > 13), $[Pt(OH)_5Cl]^{2-}$ (pH = 7-13), $[Pt(OH)Cl_5]^{2-}$ and $[Pt(OH)_2Cl_4]^{2-}$ (0.01 M HCl), 20% of $[Pt(OH)Cl_5]^{2-}$ and 80% of $[PtCl_6]^{2-}$ (0.05 M HCl). When the concentration of hydrochloric acid solution amounts to 0.1–6 M, platinum(IV) forms only one type of chlorocomplex: $[PtCl_6]^{2-}$. Studies conducted on the stability of gold(III) chloride and its species have reported that $[AuCl_4]^-$ is the predominant species in 0.1–5 M HCl [Bernardis, Grand and Sherrington 2005; Hubicki and Wójcik 2006; Zheng et al. 2012; Nikoloski and Ang 2014; Nguyen, Sonu and Lee 2016].

The effect of contact time on the percentage extraction of palladium(II), gold(III) and platinum(IV) with $[3C_6C_{14}P]BF_4$ was investigated. The contact time was varied from 1 to 60 min. The extraction of palladium(II) and gold(III) under these conditions was very fast and efficient, and equilibrium was achieved in 5 min (Fig. 1). The extraction of platinum(IV) ions is not as effective as the extraction of palladium(II) and gold(III) ions; however, despite this, further extraction experiments were carried out for 10 min.

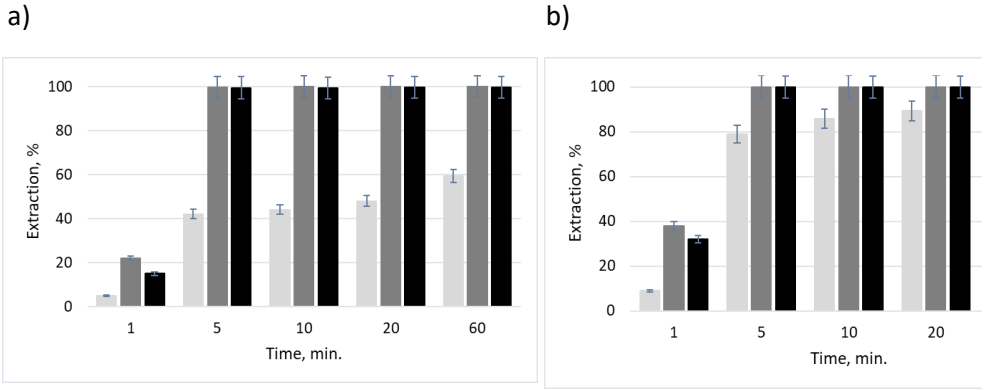

Fig. 1. Extraction of Pd(II) (■), Pt(IV) (■) and Au(III) (■) from multi-metal solution. Initial aqueous phase: [Pd(II)] = 85 mg · L^{-1}, [Au(III)] = 200 mg · L^{-1}, [Pt(IV)] = 30 mg · L^{-1} in 0.1 M HCl; organic phase: (a) 2.5 mmol · L^{-1} and (b) 5 mmol · L^{-1} $[3C_6C_{14}P]BF_4$ in toluene; A/O = 1

Source: own research.

The effect of the concentration of hydrochloric acid on palladium(II), platinum(IV) and gold(III) extraction and separation with the examined extractant was investigated (Fig. 2).

The extraction effectiveness of gold(III) does not depend on the HCl concentration and equals near 100% both with 2.5 and 5.0 mmol L^{-1}, while increasing the HCl concentration has an unfavourable influence on the palladium(II) extraction. The extent of palladium(II) extraction with 2.5 mmol · L^{-1} from 0.1 M HCl amounts to nearly 100%, while from 5.0 M HCl it decreases to approximately 73%, while the efficiency of platinum(IV) extraction increases (by about 10–24%) with the increased HCl concentration.

Palladium(II) and gold(III) species were completely extracted into the organic phase when the $[3C_6C_{14}P]BF_4$ concentration was both 2.5 and 5.0 mmol·L^{-1}. However, a change in the extractant concentration positively affected the efficiency of platinum(IV) ion extraction, reaching almost the quantitative extraction of Pt(IV) at a concentration of 5.0 mmol·L^{-1} $[3C_6C_{14}P]BF_4$ (Fig. 1 and 2). As the most preferred solution is to use the lowest concentration of extractant that produces the highest efficiency, the use of a 2.5 mmol·L^{-1} solution of $[3C_6C_{14}P]BF_4$ seems to be the best compromise both from the point of view of extraction efficiency and for economic reasons.

$[3C_6C_{14}P]BF_4$ as an extractant indicates an extraction ability towards the examined noble metal ions according to the following order: Au(III) ~ Pd(II) > Pt (IV) from 0.1 M HCl, and Au(III) > Pt(IV) ~ Pd(II) from 5 M HCl. The effectiveness and quality of separating palladium(II), platinum(IV) and gold(III) are not satisfactory, but it is possible using the stripping process.

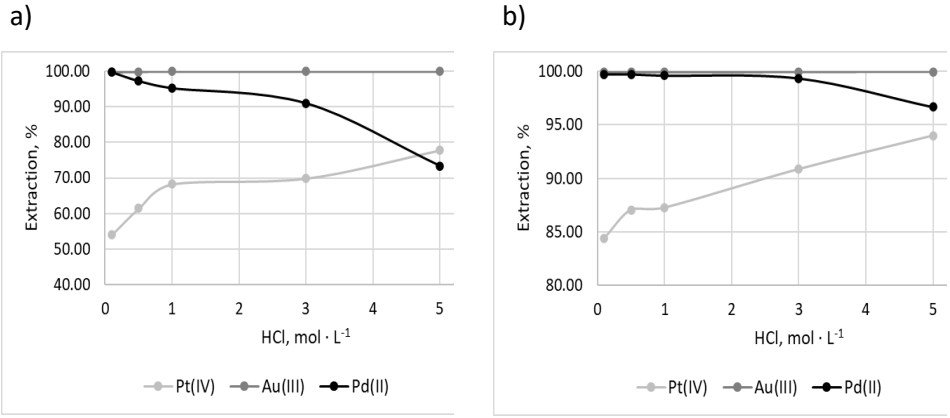

Fig. 2. Extraction of Pd(II), Pt(IV) and Au(III) from multi-metal solution. Initial aqueous phase: [Pd(II)] = 85 mg · L^{-1}, [Au(III)] = 200 mg · L^{-1}, [Pt(IV)] = 30 mg · L^{-1} in HCl (0.1–5 M); organic phase: (a) 2.5 mmol · L^{-1} and (b) 5 mmol · L^{-1} $[3C_6C_{14}P]BF_4$ in toluene; A/O = 1

Source: own research.

The organic phase loaded with metal ions should be stripped to obtain the extractant, which would be reusable in the next extraction. The stripping of palladium(II), platinum(IV) and gold(III) from the loaded organic phase was investigated (Tab. 1). The most efficient stripping of palladium(II) ions from the loaded organic phase – $[3C_6C_{14}P]BF_4$ – was achieved using 0.5 M aqueous ammonia, and the percentage of palladium(II) stripping reached nearly 100%. 3 M HNO_3 quantitatively strips platinum(IV), and complete stripping of gold(III) was possible with 0.1 M thiourea in 0.1 M HCl.

Table. 1. Stripping of palladium(II), platinum(IV) and gold(III) from loaded organic phase after extraction. Extraction: initial aqueous phase: [Pd(II)] = 85 mg · L−1, [Au(III)] = 200 mg · L−1, [Pt(IV)] = 30 mg · L−1 in 0.1 M HCl; organic phase: 2.5 mmol · L−1 [3C6C14P]BF4 in toluene

Stripping agent	Stripping percent [%]		
	Pd(II)	Pt(IV)	Au(III)
0.5 M aqueous ammonia	**98**	0	4
0.5 M ammonium thiocyanate	5	21	6
0.1 M thiourea in 0.1 M HCl	77	0	**100**
3 M HNO_3	1	**94**	0
1 M HCl	0	1	0

Source: own study.

Palladium(II), platinum(IV) and gold(III) can be successfully separated through stripping from the loaded organic phase. On the basis of the extraction-stripping data, a scheme for the recovery and separation of palladium(II),

platinum(IV) and gold(III) from 0.1 M HCl with the examined ionic liquids was proposed (Fig. 3).

30 mL of stock solution [Solution 1] of palladium(II), platinum(IV) and gold(III) in 0.1 M HCl was extracted with 2.5 mmol L−1. A portion of the platinum(IV) ions remained in the aqueous phase [Solution 2], while palladium(II), gold(III) and a portion of the platinum(IV) were transferred to the organic phase. The overwhelming majority of the remainder of the palladium(II), platinum(IV) and gold(III) were successfully stripped with 0.5 M aqueous ammonia **[Solution 3]**, 3 M HNO_3 **[Solution 4]** and 0.1 M thiourea in 0.1 M HCl **[Solution 5]**, respectively.

The compositions of the initial and final solutions are presented in Table 2.

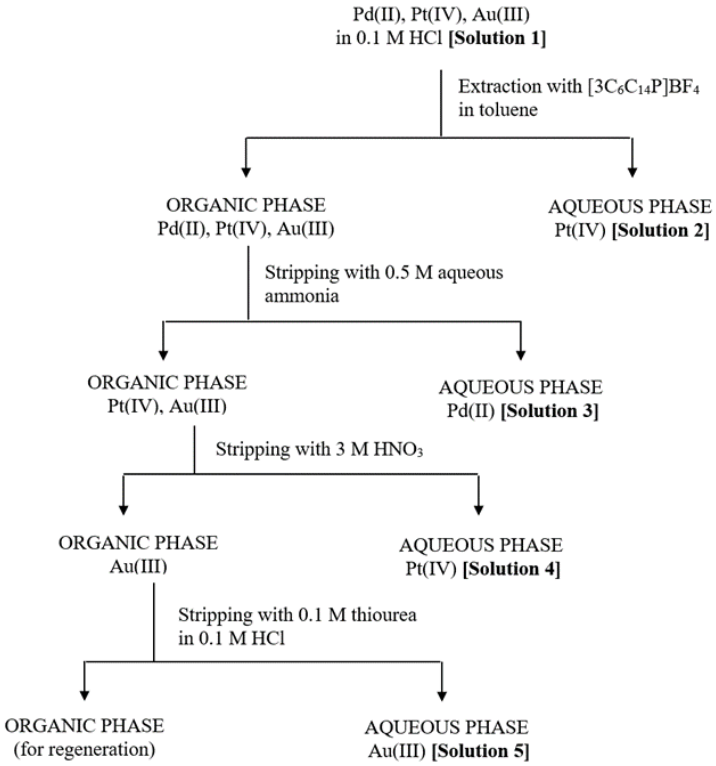

Fig. 3. Extraction of Pd(II), Pt(IV) and Au(III) from multi-metal solution. Initial aqueous phase: [Pd(II)] = 85 mg · L^{-1}, [Au(III)] = 200 mg · L^{-1}, [Pt(IV)] = 30 mg · L^{-1} in 0.1 M HCl; organic phase: 2.5 mmol · L^{-1} $[3C_6C_{14}P]BF_4$ in toluene; A/O = 1

Source: own research.

Table 2. Recovery and separation of palladium(II), platinum(IV) and gold(III) in extraction-stripping process

	Concentration of metals [mg/L]		
	Pd(II)	**Pt(IV)**	**Au(III)**
Solution 1	85.6	32.3	202.9
Solution 2	< 0.1	17.9	< 0.1
Solution 3	84.1	< 0.1	0.8
Solution 4	< 0.1	13.6	< 0.1
Solution 5	< 0.1	< 0.1	202.5
Recovery, %	**98.2**	**97.5**	**99.8**

Source: own research.

The oranic phase obtained after the extraction-stripping process according to Figure 3 was regenerated with deionised water and used again for extraction. This procedure of extraction-stripping-regeneration was repeated five times (Fig. 4).

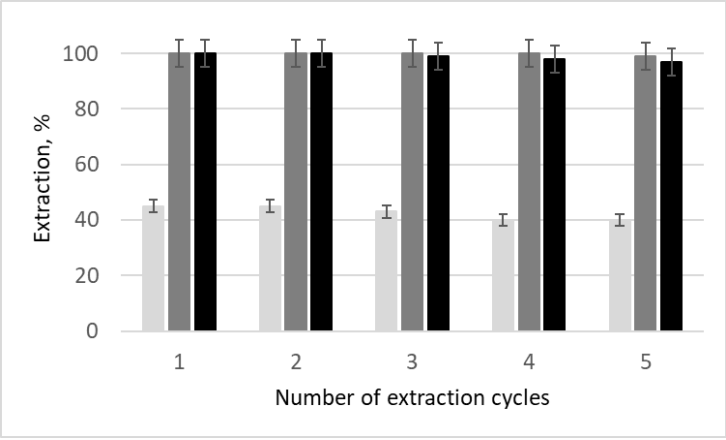

Fig. 4. Extraction of Pd(II), Pt(IV) and Au(III) from multi-metal solution with fresh (1) and regenerated (2–5) extractant. Initial aqueous phase: [Pd(II)] = 85 mg · L^{-1}, [Au(III)] = 200 mg · L^{-1}, [Pt(IV)] = 30 mg · L^{-1} in 0.1 M HCl; organic phase: 2.5 mmol · L^{-1} $[3C_6C_{14}P]BF_4$ in toluene; A/O = 1

Source: own research.

The efficiencies of palladium(II) extraction from 0.1 mol·L^{-1} HCl with both fresh and regenerated extractant are comparable, which means that $[3C_6C_{14}P]BF_4$ is a stable extractant that can be reused for the extraction of palladium(II), gold(III) and platinum(IV) because regeneration does not change its extractive properties. The regeneration of a spent organic phase is perfectly legitimate, not only because of the impact that the waste organic solutions may have on the environment but also for economic reasons, as it offers the possibility of reusing the organic reagents in subsequent extractions. This is in line with the principles of sustainable recycling, which in practice means reducing waste going to landfill, saving valuable natural

resources, minimising energy costs and achieving positive environmental, economic and social outcomes.

4. CONCLUSIONS

The ability of trihexyl(tetradecyl)phosphonium tetrafluoroborate to recover and separate palladium(II), platinum(IV) and gold(III) from hydrochloric acid solutions was studied. The results presented in this paper prove that the examined reagent can be used as an extractant for the removal of palladium(II), platinum(IV) and gold(III) ions from chloride media. The efficiency and quality of the separation of palladium(II) from platinum(IV) and gold(III) are not as effective, and depend on the acidity of the aqueous solution. The results also indicate that the extraction ability of [3C6C14P]BF4 towards the examined noble metal ions decreases according to the following order: Au(III) ~ Pd(II) > Pt (IV) from 0.1 M HCl and Au(III) > Pt(IV) ~ Pd(II) from 5 M HCl. Palladium(II), platinum(IV) and gold(III) can be successfully separated with high effectiveness and quality through stripping from the loaded organic phase. The extractant examined – [3C6C14P]BF4 – can be reused for at least 5 cycles of this extraction-stripping process without a significant loss in the extraction power, which is very desirable and beneficial from both economic and ecological points of view.

The obtained results are promising and can be used to prepare a proposal for a research methodology for the separation of precious metals, mainly palladium(II), gold(III) and platinum(IV) from real samples after leaching of waste electronic and electrical equipment (WEEE). The preliminary studies carried out on model solutions are promising, and the results obtained from the planned studies on real samples could be used in the future to improve the recovery of precious metals from e-waste, which would provide tangible economic and ecological benefits. The recycling of precious metals brings measurable ecological benefits, e.g. reducing the amount of landfilled waste, saving rare natural resources, and reducing the energy expenditure and pollutant emissions during the recovery process compared to mining in mines.

REFERENCES

Act of 11 September 2015 on waste electrical and electronic equipment, Journal of Laws 2022, item 1622, consolidated text.

Baldé, C.P., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., Bel, G., Deubzer, O., Fernandez-Cubillo, E., Forti, V., Gray, V., Herat, S., Honda, S., Iattoni, G., Khetriwal, D.S., di Cortemiglia, V.L., Lobuntsova, Y., Nnorom, I., Pralat, N., Wagner M., 2024, *International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR)*, Global E-waste Monitor 2024, Geneva/Bonn.

Bernardis, F.L., Grant, R.A., Sherrington, D.C., 2005. *A Review of Methods of Separation of the Platinum-Group Metals Through Their Chloro-Complexes,* Reactive Functional Polymers, vol. 65, pp. 205–217.

Boudesocque, S., Mohamadou, A., Conreux A., Marin, B., Dupont, L., 2019. *The Recovery and Selective Extraction of Gold and Platinum by Novel Ionic Liquids,* Separation and Purification Technology, vol. 210, pp. 824–834.

Chauhan, G., Jadhao, P.R., Pant, K.K., Nigam, K.D.P., 2018, *Novel Technologies and Conventional Processes for Recovery of Metals from Waste Electrical and Electronic Equipment: Challenges & Opportunities –A Review*, Journal of Environmental Chemical Engineering, vol. 6, pp. 1288–1304.

Cieszyńska, A., Wieczorek D., 2018, *Extraction and Separation of Palladium(II), Platinum(IV), Gold(III) and Rhodium(III) Using Piperidine-Based Extractants*, Hydrometallurgy, vol. 175, pp. 359–366.

Cieszyńska, A., Wieczorek, D., 2020, *Efficiency and Mechanism of Palladium(II) Extraction from Chloride Media with N-Hexadecylpiperidinium Chloride*, Journal of Solution Chemistry, vol. 49, pp. 486–503.

Costa, M.C., Assuncao, A., Almeida, R., da Costa, A.M.R., Nogueira, C., Paiva, A.P., 2018. *N,N'-Dimethyl-N,N'-Dicyclohexylsuccinamide: A Novel Molecule for the Separation and Recovery of Pd(II) by Liquid-Liquid Extraction,* Separation and Purification Technology, vol. 201, pp. 96–105.

Eurostat 2024, *Waste Statistics - Electrical and Electronic Equipment*, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment (access 10.04.2025).

Firmansyah, M. L., Kubota, F., Goto, M., 2018, *Solvent Extraction of Pt(IV), Pd(II), and Rh(III) with the Ionic Liquid Trioctyl (Dodecyl) Phosphonium Chloride,* Journal Chemical Technology and Biotechnology, vol. 93, no. 6, pp. 1714–1721.

Firmansyah, M.L., Rizki, I.N., Amalina, I., Jalil, A.A., Ullah, N., 2024, *Recovery of Precious Metals from Mobile Phone Waste: Studies on Leaching and Adsorption by Functionalized Activated Carbon*, Results in Engineering, vol. 22.

Gupta, B., Singh, I., 2013,. *Extraction and Separation of Palladium and Rhodium using Cyanex 923 and Their Recovery from Real Samples*, Hydrometallurgy, vol. 134–135, pp. 11–18.

He, J., Xiong Y., Xu, L., Wang, L., Yao, D., Xia, D., Tian, Y., Zhao, Z., 2022, *Selective Extraction of Pd(II) using 5,11,17,23-tetra-tert-butyl-25,26,27,28-tetra[(2-ethylthio)ethoxy]thiocalix [4] Arene as Extractant*, Journal of Environmental Chemical Engineering, vol. 10, no. 5.

Heacock, M., Kelly, C.B., Asante, K.A., Birnbaum, L.S., Bergman, A.L., Bruné, M.-N., Buka, I., Carpenter, D.O., Chen, A., Huo, X., Kamel, M., Landrigan, P.J., Magalini, F., Diaz-Barriga, F., Neira, M., Omar, M., Pascale, A., Ruchirawat, M., Sly, L., Sly, P.D., Van den Berg, M., Suk1, W.A., 2016, *E-waste and Harm to Vulnerable Populations: A Growing Global Problem*, Environmental Health Perspectives, vol. 124, no. 5, pp. 550–555.

Holgersson, S., Steenari, B.M., Björkman, M., Cullbrand, K., 2018, *Analysis of the Metal Content of Small-Size Waste Electric and Electronic Equipment (WEEE) Printed Circuit Boards, Part 1: Internet Routers, Mobile Phones and Smartphones*, Resources Conservation and Recycling, vol. 133, pp. 300–308.

Hubicki, Z., Wójcik, G., 2006. *Studies of Removal of Platinum(IV) Ion Microquantities from the Model Solutions of Aluminium, Copper, Iron, Nickel and Zinc Chloride Microquantities on the Anion Exchanger Duolite S 37*, Journal Hazardous Materials B136, pp. 770–775.

Jha, M.K.,. Gupta, D., Lee, J.-ch., Kumar, V., Jeong, J., 2014, *Solvent Extraction of Platinum Using Amine Based Extractants in Different Solutions: A Review*, Hydrometallurgy, vol. 142, pp. 60–69.

Kaliyavaradhan, S.K., Prem, P.R., Ambily, P.S., Mo, K.H., 2022, *Effective Utilization of E-Waste Plastics and Glasses in Construction Products - a Review and Future Research Directions*, Resources Conservation and Recycling, vol. 176.

Khogare, B.T., Anuse, M.A., Piste, P.B., Kokare, B.N., 2016a, *Development of a Solvent Extraction System with 4-heptylaminopyridine for the Selective Separation of Palladium(II) from Synthetic Mixture, Catalysts and Water Samples*, Desalination and Water Treatment, vol. 57, pp. 21 634–21 644.

Khogare, B.T., Kamblec, G.S., Kokarec, A.N., Zanjec, S.B., Suryavanshic, V.J., Anuse, M.A., Piste, P.B., Kokare, B.N., 2016b, *Development of Novel Solvent Extraction Method for Determination of Gold(III) using 4-heptylaminopyridine: Application to Alloys and Environmental Analysis*, Journal of Environmental Chemical Engineering, vol. 4, pp. 3075–3083.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017, *E-Waste: An Overview on Generation, Collection, Legislation and Recycling Practices*, Resources, Conservation and Recycling, vol. 122, pp. 32–42.

Kurniawan, K., Kim, S., Lee, J.-c., 2022, *Ionic Liquids-Assisted Extraction of Metals from Electronic Waste. In Ionic Liquid-Based Technologies for Environmental Sustainability*, Elsevier Amsterdam, The Netherlands, pp. 295–329.

Lim, C-R., Choi, J-W., Yun, Y-S., Cho, C-W., 2021, *Selection of Low-Toxic and Highly Efficient Ionic Liquids for the Separation of Palladium and Platinum in Acidic Solution, and Prediction of the Metal Affinity of Ionic Liquids*, Separation and Purification Technology, vol. 258.

Luhar, S., Luhar, I., 2019, *Potential Application of E-Wastes in Construction Industry: A Review*, Construction and Building Materials, vol. 203, pp. 222–240.

MacDonald, L., Zhang, D., Karamalidis, A., 2024, *Platinum Group Metals: Key Solid Phase Adsorption Technologies for Separation from Primary and Secondary Sources*, Resources, Conservation and Recycling, vol. 205.

Makvandi, S., Pagé, P., Tremblay, J., Girard, R., 2021, *Exploration for Platinum-Group Minerals in Till: A New Approach to the Recovery, Counting, Mineral Identification and Chemical Characterization*, Minerals, vol. 11, no. 3.

Matthey, J., 2024, *PGM Market Reports May*, https://matthey.com/products-and-markets/pgms-and-circularity/pgm-markets/pgm-market-reports (access 10.04.2025).

Michałek, T., Hessel, V., Wojnicki, M., 2024, *Production, Recycling and Economy of Palladium: A Critical Review*, Materials, vol. 17.

Mohdee, V., Maneeintr, K., Wannachod, T., Phatanasri, S., Pancharoen, U., 2018, *Optimization of Process Parameters using Response Surface Methodologyfor Pd(II) Extraction with Quaternary Ammonium Salt from Chloride Medium: Kinetic and Thermodynamics Study*, Chemical Papers, vol. 72, no. 12, pp. 3129–3139.

Moussaoui, S-A., Lélias, A., Braibant, B., Meyer, D., Bourgeois, D., 2021, *Solvent Extraction of Palladium(II) using Diamides: A Performing Molecular System Established Through a Detailed Study of Extraction Kinetics*, Separation and Purification Technology, vol. 276.

Mowafy, E.A., Mohamed, D., 2016, *Extraction and Separation of Gold(III) from Hydrochloric Acid Solutions using Long Chain Structurally Tailored Monoamides*, Separation and PurificationTechnology, vol. 167, pp. 146–153.

Mudal, U.K., Patil, M., Saravanabhavan, R., Saraswat, V.K., 2021, *Review on E-Waste Recycling: Part I, A Prospective Urban Mining Opportunity and Challenges*, Transactions of the Indian National Academy Engineering, vol. 6, pp. 547–568.

Müller, D., Groves, D.I., Santoshc, M., Yang, Ch-X., 2025, *Critical Metals: Their Mineral Systems and Exploration*, Geosystems and Geoenvironment, vol. 4.

Nguyen, T.H., Sonu, C.H., Lee, M.S., 2015, *Separation of Platinum(IV) and Palladium(II) from Concentrated Hydrochloric Acid Solutions by Mixtures of Amines with Neutral Extractants*, Journal of Industrial and Engineering Chemistry, vol. 32, pp. 238–245.

Nguyen, T.H., Sonu, C.H., Lee, M.S., 2016, *Separation of Pt(IV), Rh(III) and Ir(III) from Concentrated Hydrochloric Acid Solutions by Solvent Extraction*, Hydrometallurgy, vol. 164, pp. 71–77.

Nguyen, V.T., Riaño, S., Aktan, E., Deferm, C., Fransaer, J., Binnemans, K., 2021, *Solvometallurgical Recovery of Platinum Group Metals from Spent Automotive Catalysts*, ACS Sustainable Chemistry Engineering Journal, vol. 9, pp. 337–350.

Nguyen, V.T., Riaño, S., Binnemans, K., 2020, *Separation of Precious Metals by Split-Anion Extraction using Water-Saturated Ionic Liquids*, Green Chemistry, vol. 22, pp. 8375–8388.

Nikoloski, A.N., Ang, K.L., 2014, *Review of the Application of Ion Exchange Resins for the Recovery of Platinum-Group Metals from Hydrochloric Acid Solution*, Mineral Processing Extractive Metallurgy Review, vol. 35, pp. 369–389.

Ortet, O., Paiva, A.P., 2015, *Development of Tertiary Thioamide Derivatives to Recovery Palladium(II) from Simulated Complex Chloride Solutions*, Hydrometallurgy, vol. 151, pp. 33–41.

Paiva, A.P., Piedras, F.V., Rodrigues, P.G., Nogueira, C.A., 2022, *Hydrometallurgical Recovery of Platinum-Group Metals from Spent Auto-Catalysts – Focus on Leaching and Solvent Extraction*, Separation and Purification Technology, vol. 286.

Rzelewska-Piekut, M., Paukszta D., Regel-Rosocka, M., 2021, *Hydrometallurgical Recovery of Platinum Group Metals from Spent Automotive Converters*, Physicochemical Problems at Mineral Processing, vol. 57, pp. 83–94.

Rzelewska-Piekut, M., Regel-Rosocka, M., 2019, *Separation of Pt(IV), Pd(II), Ru(III) and Rh(III) from Model Chloride Solutions by Liquid-Liquid Extraction with Phosphonium Ionic Liquids*, Separation and Purification Technology, vol. 212, pp. 791–801.

Sasaki, Y., Morita, K., Morihisa, S., Hisamatsu, S., Yoshizuka, K., 2017, *Presious Metal Extraction by N,N,N',N'-Tetraoctyl-Thiodiglycolamide and Its Comparision with N,N,N',N'-tetraoctyl-diglycolamide and methylimino-N,N'-dioctylacetamide*, Hydrometallurgy, vol. 169, pp. 576–584.

Song, L., Wang, X., Li L., Wang, Z., Xu, H., He, L., Li, Q., Ding, S., 2022, *Recovery of Palladium(II) from Strong Nitric Acid Solutions Relevant to High-Level Liquid Waste of PUREX Process by Solvent Extraction with Pyrazole-Pyridine-Based Amide Ligands*, Hydrometallurgy, vol. 211.

Statista, https://www.stati sta.com (access 10.04.2025).

We, W., Cho, C.-W., Kim, S., Song, M.-H., Bediako, J.K., Yun, Y.-S., 2016, *Selective Recovery of Au(III), Pt(IV), and Pd(II) from Aqueous Solutions by Liquid–Liquid Extraction using Ionic Liquid Aliquat-336*, Journal of Molecular Liquids, vol. 216, pp. 18–24.

Wiecka, Z., Rzelewska-Piekut, M., Reis, M.T.A., Ismael, M.R.C., Wieszczycka, K., Regel-Rosocka, M., 2023, *Pd(II) and Pt(IV) Dispersive or Non-Dispersive Extraction from Model and Real Leach Solutions with Alkoxyimine-1-propylpyridinium Derivatives*, Separation and Purification Technology, vol. 317.

World Gold Council, 2024, *Gold Demand Trends: Full Year 2024*, https://www.gold.org/goldhub/research/gold-demand-trends/gold-demand-trends-full-year-2024 (access 10.04.2025).

Xiao, Q., Song, L., Wang, X., Xu, H., He, L., Li, Q., Ding, S., 2022, *Highly Efficient Extraction of Palladium(II) in Nitric Acid Solution by a Phenanthroline-Derived Diamide Ligand*, Separation and Purification Technology, vol. 280.

Yakoumis, I., Panou, M., Moschovi, A.M., Panias, D., 2021, *Recovery of Platinum Group Metals from Spent Automotive Catalysts: A Review*, Cleaner Engineering and Technology, vol. 3.

Zhang, L., Xu, Z., 2016, *A Review of Current Progress of Recycling Technologies for Metals from Waste Electrical and Electronic Equipment*, Journal of Cleaner Production, vol. 127, pp. 19–36.

Zheng, H., Hu D., Zhang, L., Ma, C.A., Rufford, T., 2012, *Thiol Functionalized Mesoporous Silicas for Selective Adsorption of Precious Metals*, Minerals Engineering, vol. 35, pp. 20–26.

Zulkernain, N.H., Basant, N., Ng, C.C., Salari, M., Mallick, S., 2023, *Recovery of Precious Metals from E-Wastes through Conventional and Phytoremediation Treatment Methods: A Review and Prediction*, Journal of Material Cycles and Waste Management, vol. 25, pp. 2726–2752.