

Article

Adsorption of Platinum from Alkaline Glycine–Cyanide Solutions Using Activated Carbon: Leachates, Water, and Waste Treatment Applications

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Abstract

Platinum's unique properties, such as its high resistance to corrosion and high temperatures, are driving an increased use in modern technologies and advanced chemistry. However, the World Platinum Investment Council has projected, for the third consecutive year, a global deficit of platinum for 2025 and a negative forecast until 2029, highlighting the need for the development of new metallurgical methodologies to recover platinum but also to recycle product containing it. The use of alkaline amino acid (glycine) promises a highly selective and more environmentally friendly recovery methodology. Over the Platinum Group Metals, recovery studies have been performed only on palladium, but no published literature over platinum was found. This study investigated the feasibility of platinum adsorption from alkaline glycine solutions under various operational conditions using activated carbon. Results are demonstrating that platinum can be successfully recovered under the effects tested: 92.37–97.93% (carbon dosage), 70.00–95.72% (temperature), 94.08–97.39% (pH), 95.16–96.23% (platinum concentration), 95.72–96.53% (glycine concentration), and 95.72–97.12% (cyanide concentration). The scientific significance of this study lies in the confirmation for the potential use of a more environmentally friendly approach to recover platinum as opposed to the current cyanide and acidic chloride system.

Keywords: PGM; platinum; glycine; adsorption; activated carbon; kinetic



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1. Introduction

The World Platinum Investment Council is projecting, for the third consecutive year, a deficit of platinum (Pt) for 2025 and a negative forecast until 2029 (annual average deficit of 727 koz) [1]. Platinum's high corrosion resistance, chemical inertness, and ability to resist high temperatures offer unique catalytic properties in critical chemical and electrochemical processes, increasing its applications in modern technologies and advanced chemistry, such as vehicle catalytic converters, fuel cells, biomedical industry, and jewelry, amongst others [2].

From a geological perspective, platinum is a scarce metal, and its main mining producers in the world (2023) are located in South Africa (69%), Russia (13%), and Zimbabwe (11%) [3,4]. Recent reports on Critical Raw Materials and the Circular Economy of the European Union have declared PGMs as scarce raw materials and established goals of recycling rates for their industrial use, allowing a circular economy [5,6]; this is also an

incentive for mining companies to develop new processes to extract it from secondary sources as leaching and waste solutions [7].

The development of hydrometallurgical methodologies to recover Pt have been closely linked to the practices implemented in gold, specifically recovery processes from cyanide solutions utilizing activated carbon [8,9].

Separation and purification technologies, such as solvent extraction (SX) and ion exchange (IX), are now well-established methods in the refining industry for PGMs [10]. Studies investigating the application of IX and activated carbon to recover precious metal from cyanide complexes have been reported, extending the scope beyond the traditional chloro-complex-based metallurgical approaches [8,9,11].

Activated carbon (from different sources as coconut shells or derived from biomass residues, among others) is widely known in the extraction industry for its porous structure, large surface area, ecofriendly nature, and high purity standard that facilitate adsorption processes. It has been commonly used to recover gold from cyanide leachates because of its reliability, recovery rates, and low capital and operation cost requirements [12–14].

In the last decade, the use of amino acids, such as glycine, has been patented and published as an alternative lixiviant for precious metals (gold) and base metals (copper). This alkaline–amino acid leaching method offers a highly selective and environmentally friendly alternative to the current cyanide and chlorine systems for metals extraction [15,16].

Studies have demonstrated the effectiveness of activated carbon in recovering gold in the presence of copper (99% and 53% recovery, respectively, in 24 h test) from cyanide-starved glycine synthetic solutions [17] and glycine-only systems (99% and 15% recovery, respectively, in 24 h test) [18]. Also, adsorption results using activated carbon on gold and silver glycines suggest the loading potential from alkaline glycine solutions ($13.2 \text{ kg Au/t carbon}$ and $3.4 \text{ kg Ag/t carbon}$) [19].

Rubina et al., 2025, demonstrated the feasibility of palladium adsorption from glycine–cyanide solutions using activated carbon, achieving Pd recovery rates between 92.7% and 98.2% [20]. These results represented the opportunity to extend the evaluation to other elements in the Platinum Group Metals (PGMs), like platinum, for which no research has been published in the literature.

The objective of this research is to assess the feasibility of platinum adsorption from synthetic alkaline glycine–cyanide leach solutions under various operational conditions (initial Pt, concentrations of glycine and cyanide, carbon dosage, and pH and temperature) using activated carbon.

The novelty of this study is related to the opportunity assessment of using a more environmentally friendly approach to recover Pt from alkaline glycine–cyanide solutions over the current cyanide methodology used to recover Pt and PGMs.

Before other systems, such as leachates from minerals, e-waste, or catalytic converter waste, can be studied, the behavior of the simplified system needs to be understood in the absence of other interfering parameters of multi-metallic systems with impurities. It is, therefore, the aim of this research to present this foundational information and quantify and characterize the adsorption phenomena from a process engineering perspective.

2. Experimental Design—Materials and Methods

2.1. Adsorbent (Activated Carbon)

Untreated activated carbon (Haycarb YAO 60, Colombo, Sri Lanka), derived from coconut shells, 16–27% typical butane activity, 0.48 g/cc apparent density, 3% ash content, and 2% wet attrition loss was used in the tests, with a surface area of $648 \pm 15 \text{ m}^2/\text{g}$, determined following the Brunauer–Emmett–Teller (BET) method, using nitrogen adsorption–

desorption isotherms at 77 K. The analysis was performed with a Micromeritics ASAP 2020 analyzer (Norcross, GA, USA) after degassing the samples at 200 °C for 15 h.

Figure 1 shows a Scanning Electron Microscope (SEM) image of the fresh activated carbon (Tescan Mira3, Tescan, Czech Republic, John de Laeter Centre, Curtin University, Western Australia). Image shows an irregular (rough) external surface with a dense and complex network of pores, cracks, and sharp edges of various sizes. Table 1 summarizes its granulometric specifications (particle size distribution).

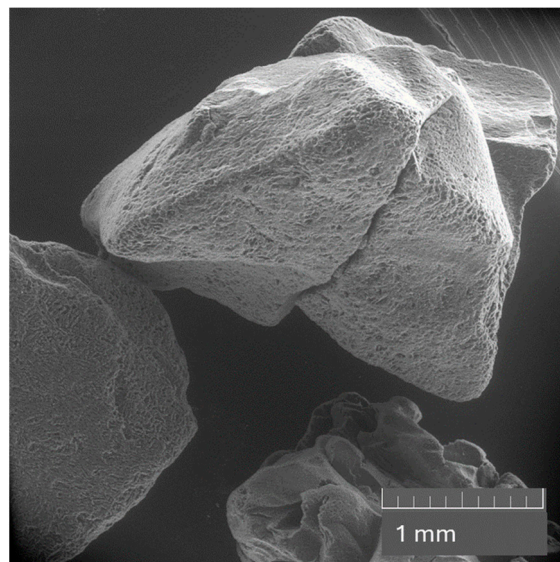


Figure 1. Scanning Electron Microscope (SEM) picture of the fresh activated carbon (Haycarb YAO 60).

Table 1. Granulometric specifications (particle size distribution) of the fresh activated carbon.

Screen Aperture (mm)	+3.35	+2.80	+2.36	+2.00	+1.70	+1.40	+1.00	−1.00	Total	D ₅₀ , mm
% weight retained (Haycarb YAO 60)	2.4	22.6	41.0	27.2	6.2	0.4	0	0.1	100	2.6

2.2. Synthetic Glycine–Cyanide Solution

This research was performed using a synthetic glycine–cyanide stock solution (1 L), prepared by dissolving glycine ($\geq 99\%$, Sigma-Aldrich, Merck, Perth, Australia) in deionized (DI) water sourced by Curtin University, Perth, Australia. The pH of the solution was adjusted to pH 10.5 using sodium hydroxide (NaOH, 5–50%*w/w*, Rowe Scientific, Perth, Australia), with pH measurements taken using a pH meter (model of 90-FLMV, TPS, Brendale, Australia). After pH adjustment, cyanide (NaCN, Rowe Scientific, Perth, Australia, $>99\%$ purity) and platinum powders (99.9% purity, Sigma-Aldrich, Merck, Perth, Australia) were added according to the concentrations outlined in Table 2. The solution was then agitated at 300 rpm for 96 h in a reactor at 50 °C, while oxygen was sparged into the reactor at 0.1 L/min following similar conditions, as published by Tauetsile et al., 2019, for the adsorption of gold from starved cyanide glycinate leachates [17,18].

Table 2. Characterization of the synthetic 1 L glycine–cyanide stock solution.

Parameters	Conditions	Unit
[Pt]	241.5	mg/L
pH	10.5	
[Gly]	30,000	mg/L
[CN]	3000	mg/L

2.3. Adsorption Experiments

Adsorption tests were performed in a heated shaking bath (Ratek SWB20D, Melbourne, Australia) using 500 mL glass flasks. Each flask contained 250 mL of synthetic glycine–cyanide solution, which was diluted with DI water. According to the test conditions, glycine, cyanide, and activated carbon were added. The solutions were shaken in the presence of carbon at 100 rpm for 24 h at the specified temperature. Samples of 5 mL were taken from each flask using a syringe at 0.75, 2, 4, 6, and 24 h and then filtered with a FilterBio Ca (Nantong, China), (0.22 µm pore size) to remove the presence of any fine carbon particles and prevent additional adsorption.

Table 3 contains the parameters and conditions used to determine the impact over Pt adsorption, where [Pt] = 5 mg/L, [CN] = 300 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 10 g/L, and temperature = 24 °C have been considered as standard conditions, based on previous work performed at Curtin University [17,18].

Table 3. Summary of parameters and conditions to test Pt adsorption.

Parameters	Conditions	Unit
Carbon dosage	5–10 *–20	g/L
Temperature	24 *–35–55	°C
pH	9.5–10.5 *–11.5	
[Pt]	2–5 *–10	mg/L
[Gly]	1000–3000 *–5000	mg/L
[CN]	100–300 *–500	mg/L

Note: * is considered as standard condition.

The metal recovery was calculated using Equation (1) [12,21]:

$$\text{Metal Recovery (\%)} = \left(\frac{C_o - C_t}{C_o} \right) \times 100\% \quad (1)$$

where C_o is the initial metal concentration (mg/L), and C_t (mg/L) is the metal concentration at time t .

The amount of metal adsorbed onto the adsorbent (Q_e , mg/g) at equilibrium was calculated by Equation (2):

$$Q_e = \frac{(C_o - C_e) \times V}{W} \quad (2)$$

where C_e is the metal concentration at equilibrium (mg/L), V is the solution volume (L), and W is the mass of dry carbon (g) [21].

2.4. Reaction Mechanism and Kinetics

2.4.1. Kinetics Modeling

Adsorption kinetics models have been widely used to assess the kinetic behavior of adsorbates on adsorbents. The pseudo-first-order (PFO) model assumes that the rate of adsorption is proportional to the number of unoccupied sites on the adsorbent surface

(with physisorption limiting the rate), while the pseudo-second-order (PSO) equation is based on the sorption capacity of the solid phase [22,23].

After integration and applying boundary condition ($Q_t = 0$ at $t = 0$), pseudo-first-order kinetic model is expressed as follows [21,23]:

$$\log(Q_e - Q_t) = \log Q_e - \frac{K_1}{2.303} t \quad (3)$$

where Q_t is the amount of adsorbate on the surface of adsorbent at the time (mg/g), Q_e is the amount of the adsorbed at equilibrium (mg/g), K_1 is the equilibrium constant of the pseudo-first-order adsorption (h^{-1}), and K_2 is the equilibrium rate constant of the pseudo-second-order model ($\text{g/mg} \times \text{h}$).

The integrated form for the pseudo-second-order kinetic model is defined as follows [21,24]:

$$\frac{t}{Q_t} = \left(\frac{1}{K_2 Q_e^2} \right) + \left(\frac{t}{Q_e} \right) \quad (4)$$

The adsorption kinetic tests were performed under different concentrations of activated carbon (condition of carbon excess). The samples were collected at different time intervals to analyze the metal ions concentration (mg/L) and the amount of metal adsorbed at time t (Q_t). The adsorption kinetic process was determined using experimental data, evaluating the best correlation with pseudo-first-order and pseudo-second-order models through linear regression.

2.4.2. Isotherm Study

To characterize the adsorption process at equilibrium, Freundlich and Langmuir adsorption isotherm models are commonly applied and evaluated based on the model that best fits the data. The parameters calculated in the regression are used to estimate the quantity of metal ions adsorbed onto the carbon at equilibrium (Q_e).

In this research, the adsorption isotherms were designed to find the capacity limit, testing three different Pt concentrations (2, 5, and 10 mg/L) at five different mass to volume ratios of carbon (0.5, 2, 5, 10, and 20 g/L) in 250 mL synthetic glycine–cyanide solutions for 24 h.

The Freundlich isotherm model is expressed as follows [12,21]:

$$Q_e = K_f C_e^{1/n} \quad (5)$$

$$\log Q_e = \log K_f + \frac{1}{n} \log C_e \quad (6)$$

where K_f ($(\text{mg/g})/(\text{mg/L})^{1/n}$) is the equilibrium adsorption capacity, C_e is the metal concentration at equilibrium (mg/L), and n is the equation constant, representing the deviation from linearity of adsorption.

The linear Langmuir model is presented as follows [21,25]:

$$\frac{1}{Q_e} = \left(\frac{1}{Q_m} \right) + \left(\frac{1}{K_L Q_m} \right) \left(\frac{1}{C_e} \right) \quad (7)$$

where K_L is Langmuir equilibrium adsorption constant (L/mg), and Q_m (mg/g) is the maximum adsorption capacity estimated by the Langmuir model.

The published literature suggests calculating separation factor (R_L) [21,26]:

$$R_L = \frac{1}{(1 + K_L C_o)} \quad (8)$$

The values of $R_L > 1$, $R_L = 1$ and $R_L < 1$ reflect that the adsorption is unfavorable, linear, and favorable, respectively.

Finally, the experimental data were assessed using these two regression models to determine the best fit and draw conclusions.

2.5. Analytical Methods

The assays were performed at Bureau Veritas (Perth) using an Inductively Coupled Plasma Mass Spectroscopy (instrument Agilent 7900 ICP-MS, Agilent Technologies Inc., Santa Clara, CA, USA). Samples were diluted using 10% hydrochloric acid (HCl), and the ICP measurements were performed in conjunction with multi-element calibration solutions prepared at concentrations of 1 mg/L and 10 mg/L using a certified platinum 1000 mg/L stock solution prepared by High-Purity Standards (Charleston, SC, USA). The operational conditions included Argon (plasma gas), micromist (nebulizer), peltier-cooled double-pass quartz (spray chamber), quartz with 2.5 mm injector (torch), standard acquisition mode, and operated in standard mode for Pt (collision/reaction cell).

2.6. Statistical Analysis

An Analysis of Variance (ANOVA) was performed using the software Design Expert (2024) to determine the impact of the different sources of variation over the experimental data [27,28].

2.7. Quality Assurance and Quality Controls (QA/QC)

A comprehensive QAQC program was designed and implemented to verify the reproducibility of the samples collected from the stock solution but also from the sampling protocol utilized (Figure 2). Triplicate samples were collected from the stock solution to monitor and quantify the process reproducibility, and duplicate samples were collected at the different test times to verify sampling reproducibility [29,30].

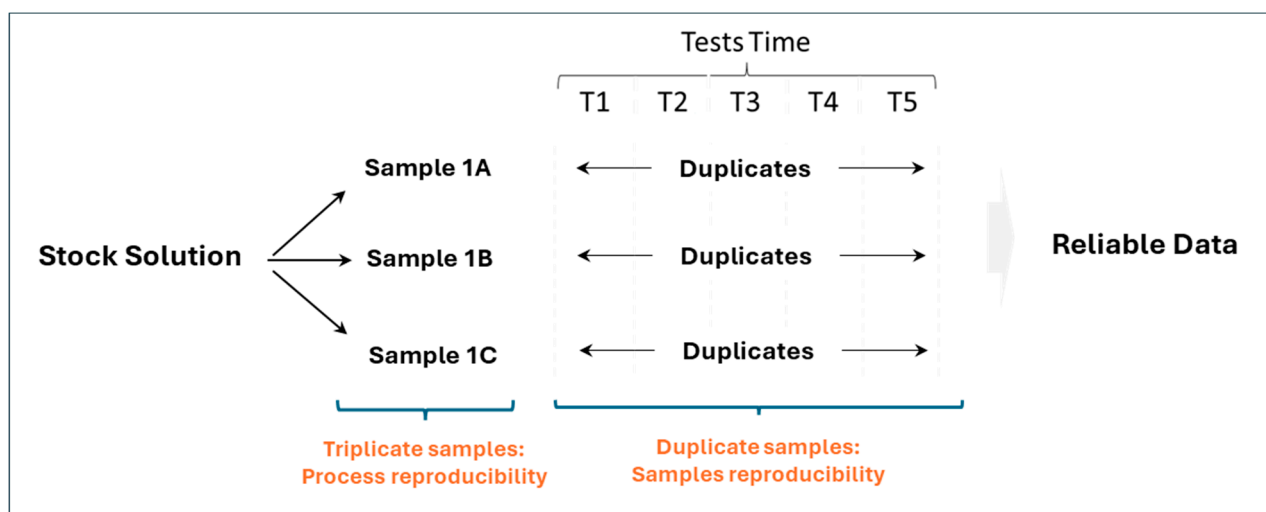


Figure 2. Scheme showing the quality program QAQC designed to monitor the process and samples reproducibility.

3. Results and Discussions

3.1. Platinum Adsorption Using Activated Carbon (Standard Conditions)

Results in Figure 3 show that activated carbon can efficiently adsorb Pt from a synthetic alkaline glycine–cyanide solution. The adsorption kinetic, at standard conditions, showed a fast kinetic in the first 45 min measurement (61.87%) and subsequently achieved 92.3% Pt

recovery within 6 h of the test, where a system equilibrium plateau is interpreted. After 24 h, the adsorption increased a further 3.59%, reaching a final Pt recovery of 95.72%.

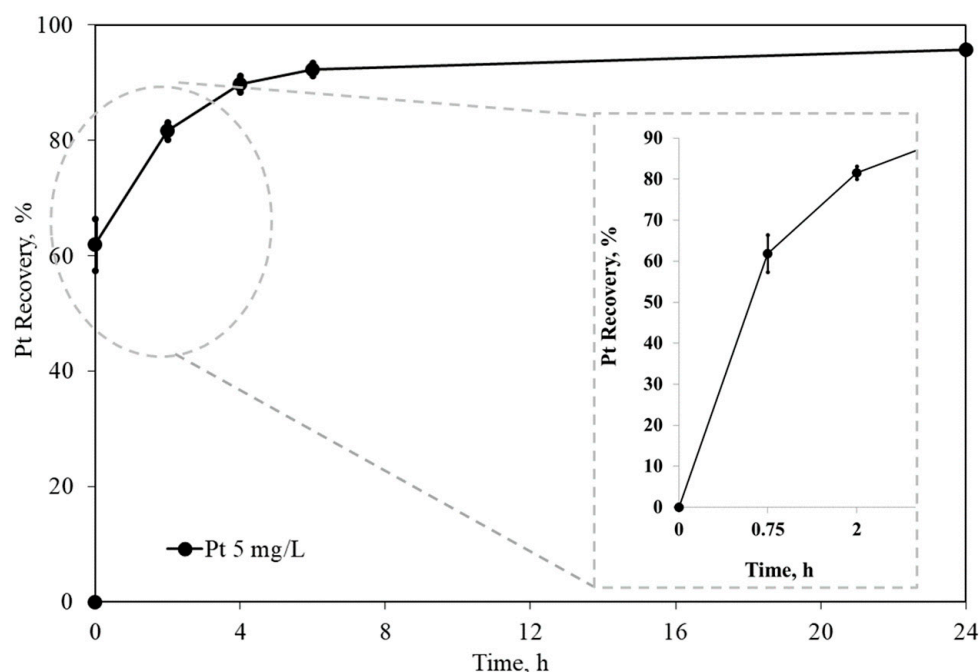


Figure 3. Platinum adsorption using activated carbon. Standard conditions: Pt = 5 mg/L, [CN] = 300 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 10 g/L, and ambient temperature (24 °C). Error bars represent 2 standard deviations—95% confidence.

Triplicate samples collected to quantify the process variability are presented as an error bar in Figure 3, representing two standard deviations. The overall error obtained was 1.54% (95% confidence).

These positive adsorption results were used as a baseline to test the impact of different operating conditions on Pt recovery.

3.2. Kinetic Modeling

The experimental data was assessed under various test conditions (Table 3), and results obtained have shown a good fit with a pseudo-second-order kinetic model. The pseudo-second-order kinetic model is based under the assumption of the rate-limiting step being chemical sorption or chemisorption, predicting the response over the entire range of adsorption.

3.2.1. Effect of Carbon Dosage

Tests were conducted to understand and evaluate the importance of the carbon dosage on the overall adsorption and kinetics rate. According to the literature, carbon dosage can play an important role in the adsorption performance related to its adsorption sites per unit mass: a higher amount of carbon will increase its adsorption amount towards Pt [13].

The effect of different carbon dosages over Pt recovery was investigated. Tests were performed at 5 g/L, 10 g/L, and 20 g/L of carbon. The results are presented in Figure 4 and Table 4.

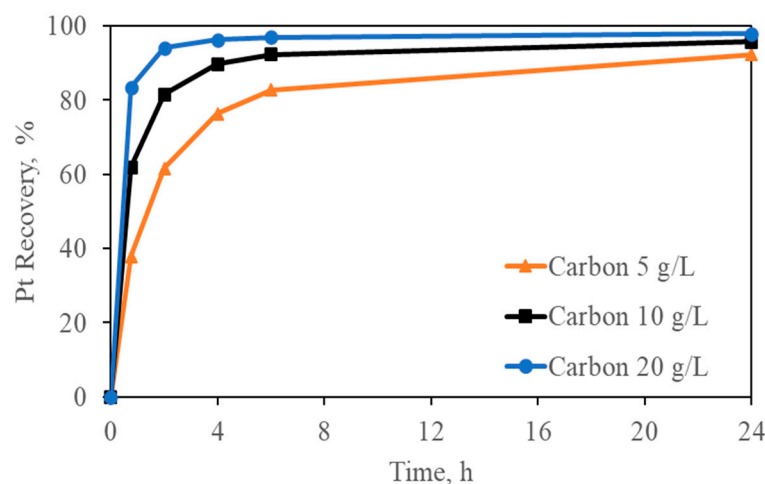


Figure 4. Effect of varying initial carbon dosages on Pt recovery (Pt-pure solution over carbon). Experimental conditions: Pt = 5 mg/L, [CN] = 300 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 5–10–20 g/L, and temperature = 24 °C.

Table 4. Kinetic model parameters determined at varying carbon dosages.

Kinetic Model	Parameters	Carbon Dosage (g/L)	
		10	20
Pseudo-first order	Q_e , Cal (mg/g)	0.14	0.03
	K_1 , (h^{-1})	0.18	0.24
	R^2	0.82	0.63
Pseudo-second order	Q_e , Exp (mg/g)	0.48	0.25
	Q_e , Cal (mg/g)	0.48	0.25
	K_2 (g/mg×h)	7.82	55.02
	R^2	0.99	0.99

Figure 4 shows that the Pt recoveries obtained were $92.37\% \pm 0.80\%$, $95.72\% \pm 0.77\%$, and $97.93\% \pm 0.66\%$ at a 5 g/L, 10 g/L, and 20 g/L carbon dosage, respectively. The highest Pt recovery achieved, at the highest carbon dosage used, is interpreted to be directly related to the increased number of adsorption sites available for adsorbing Pt from the solutions. In addition, the differences in recovery rates achieved across the varying conditions highlight the impact of the carbon dosage over the kinetics of the adsorption process, where the curves for 10 g/L and 20 g/L are interpreted as achieving an equilibrium plateau. These results are consistent with the constant K_2 , determined from Equation (4), which show results from the highest carbon dosage of 20 g/L to the lowest at 5 g/L (Table 4).

The trends in the kinetics of the adsorption results for Pt using activated carbon are similar to those obtained by Rubina et al., 2025, who tested carbon dosages between 5 g/L and 20 g/L, increasing the Pd recovery from 89% to 98.2%, and Tauetsile et al., 2019, who tested carbon dosages from 2 g/L to 12 g/L, increasing the gold recovery from 88% to 99% [17,20].

These results have demonstrated the significant influence of the carbon dosage on Pt recovery and kinetics, where the metals' recovery efficiency increased with the increasing carbon concentration.

Table 4 shows the kinetic model parameters determined at the different carbon dosages tested. The results show a high correlation with a pseudo-second-order model, with similar results between the Q_e experimental and the Q_e calculated.

3.2.2. Effect of Temperature

The effect of temperature over Pt recovery was investigated. Tests were performed at 24 °C, 35 °C, and 55 °C. Results are presented in Figure 5 and Table 5.

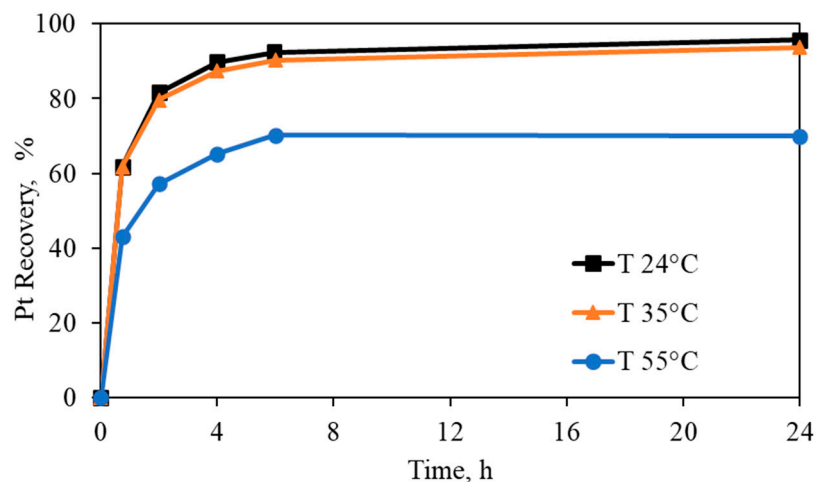


Figure 5. Effect on Pt recovery at different temperatures (Pt-pure solution over carbon). Experimental conditions: Pt = 5 mg/L, [CN] = 300 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 10 g/L, and temperature = 24–35–55 °C.

Table 5. Kinetic model parameters determined at various temperatures.

Kinetic Model	Parameters	T (°C)		
		24	35	55
Pseudo-first order	Q_e , Cal (mg/g)	0.14	0.10	0.17
	K_1 , (h^{-1})	0.18	0.22	0.12
	R^2	0.82	0.88	0.50
Pseudo-second order	Q_e , Exp (mg/g)	0.48	0.47	0.36
	Q_e , Cal (mg/g)	0.48	0.47	0.35
	K_2 , (g/mg×h)	7.82	7.77	7.61
	R^2	0.99	0.99	0.99

Figure 5 shows the Pt recovery achieved over a 24 h test at different temperatures (24–35–55 °C). The results ($95.72\% \pm 0.77\%$, $93.78\% \pm 0.19\%$, and $70.00\% \pm 0.59\%$, respectively) indicate that the highest Pt recovery was obtained at 24 °C, where all the conditions tested have been interpreted as achieving an equilibrium plateau. This trend is consistent with the highest K_2 constant achieved in the kinetic model (Table 5) at this temperature.

Pt adsorption results show a decreasing performance when the temperature is increased from 24 °C to 55 °C. This trend is consistent with the results obtained by Rubina et al., 2025, over Pd in glycine–cyanide solutions (>90% versus 67% Pd recovery at 24 °C and 55 °C, respectively) and Ladeira et al., 1993, for gold in cyanide solutions (~90% versus ~50% Au recovery at 25 °C and 80 °C, respectively) [20,31]. In these studies, results suggested a significant impact of the temperature over the Pt, Pd, and Au recovery, where higher temperatures reduced the adsorption efficiency.

The diminution of the adsorption could be explained by an enhancement of the desorption rate due to a greater kinetic energy to molecules ratio developed at higher temperatures. This characteristic could be used towards the thermal stripping of these metals from loaded activated carbon (as is the case for gold).

Table 5 shows the kinetic model parameters determined at the different temperatures tested. Results show a high correlation with a pseudo-second-order model, with similar values between the experimental Q_e and the calculated Q_e .

3.2.3. Effect of pH

The effect of pH on Pt recovery was investigated. The 24 h tests were performed at pH 9.5, 10.5, and 11.5. The results are presented in Table 6 and Figure 6.

Table 6. Kinetic model parameters determined at different pHs.

Kinetic Model	Parameters	pH		
		9.5	10.5	11.5
Pseudo-first order	Q_e , Cal (mg/g)	0.12	0.14	0.17
	K_1 , (h^{-1})	0.11	0.18	0.13
	R^2	0.52	0.82	0.77
Pseudo-second order	Q_e , Exp (mg/g)	0.50	0.48	0.48
	Q_e , Cal (mg/g)	0.49	0.48	0.48
	K_2 , ($\text{g}/\text{mg} \times \text{h}$)	9.49	7.82	5.14
	R^2	0.99	0.99	0.99

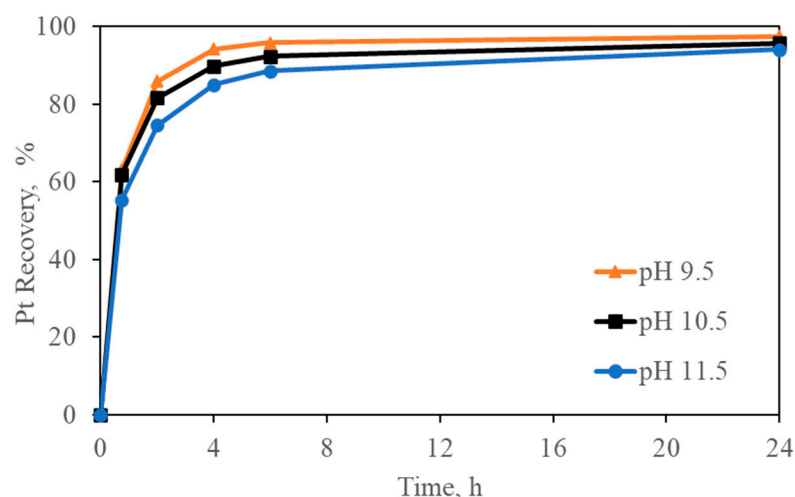


Figure 6. Effect on Pt recovery at different initial pH (Pt-pure solution over carbon). Experimental conditions: Pt = 5 mg/L, [Gly] = 3000 mg/L, [CN] = 300 mg/L, pH = 9.5–10.5–11.5, carbon dosage = 10 g/L, and temperature = 24°.

Pt recoveries obtained from the 24 h test at pH 9.5, pH 10.5, and pH 11.5 were $97.39\% \pm 0.37\%$, $95.72\% \pm 0.77\%$, and $94.08\% \pm 1.64\%$, respectively, (a decreasing recovery trend as the pH increased). In addition, the curves for all the conditions tested were interpreted as achieving an equilibrium plateau. These trends are consistent with the constant K_2 determined in the kinetic model (Table 6), where the highest recovery correlates with the highest K_2 calculated.

The higher Pt recovery at the lower pH tested (9.5) is similar to the results obtained by Rubina et al., 2025, over palladium from the glycine–cyanide system, suggesting that lower pH levels generate better conditions for adsorption [20]. According to Petersen and Van Deventer, 1991, hydronium ions participate in carbon surface oxidation, which, in conjunction with oxygen, improves the loading capacity of the carbon, where a greater surface oxidation leads to a higher adsorption capacity in the carbon [32]. Furthermore,

Faghirinejad et al., 2025, found that a reduction in gold adsorption when pH is increased could be related to the decrease in active sites on the surface of the carbon due to an increase in the concentration of hydroxide ions [33]. This could explain why these ions tend to increase and compete with platinum complexes over the carbon surface at high pHs.

Finally, Pt recovery results (87% at pH 12 and 90% at pH 9.5) obtained by Snyders et al., 2013, in a 72 h test and using similar concentrations of carbon in a mix precious and base metals solution, concluded that pH 9.5 was more favorable for PGM adsorption in the cyanide system [9].

Table 6 summarizes the kinetic model parameters at different pH levels. The results show that the higher K_2 correlates with the highest adsorption achieved (pH 9.5) and a strong correlation with the pseudo-second-order model.

3.2.4. Effect of Initial Pt Concentration

The effect of the initial Pt concentration was investigated. Different tests were performed for 24 h at 2 mg/L, 5 mg/L, and 10 mg/L concentrations. The results are shown in Figure 7 and Table 7.

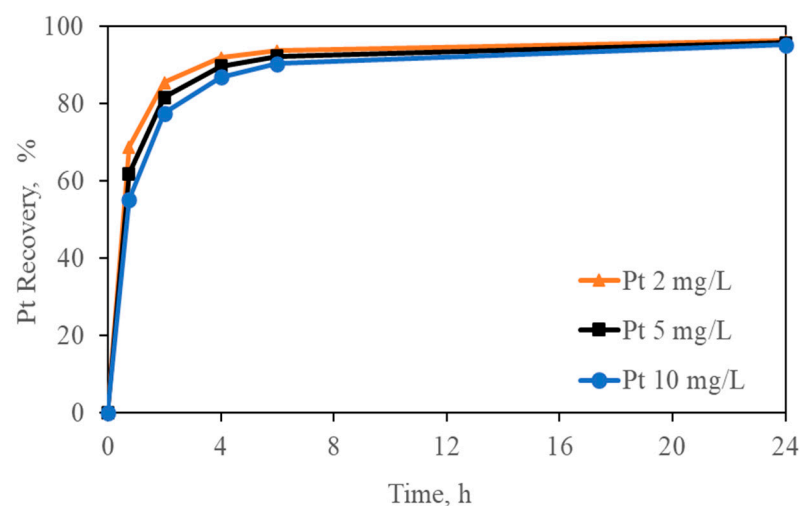


Figure 7. Effect of different initial Pt concentrations on Pt adsorption (Pt-pure solution over carbon). Experimental conditions: Pt = 2–5–10 mg/L, [Gly] = 3000 mg/L, [CN] = 300 mg/L, pH = 10.5, carbon dosage = 10 g/L, and temperature = 24 °C.

Table 7. Kinetic model parameters determined at different Pt concentrations.

Kinetic Model	Parameters	Pt (mg/L), t = 0		
		2	5	10
Pseudo-first order	Q_e , Cal (mg/g)	0.05	0.14	0.33
	K_1 , (h^{-1})	0.10	0.18	0.13
	R^2	0.52	0.82	0.75
Pseudo-second order	Q_e , Exp (mg/g)	0.20	0.48	0.97
	Q_e , Cal (mg/g)	0.19	0.48	0.97
	K_2 , (g/mg×h)	24.26	7.82	2.74
	R^2	0.99	0.99	0.99

Figure 7 shows the adsorption kinetic and Pt recovery achieved during the 24 h test at different initial Pt concentrations. Pt recoveries obtained were $96.23\% \pm 0.62\%$ (2 mg/L), $95.72\% \pm 0.77\%$ (5 mg/L), and $95.16\% \pm 0.30\%$ (10 mg/L). The similarity in the results

suggests that the overall Pt extraction is not significantly affected by the initial concentration of the metal in the solution, which is consistent with the results obtained by Fleming et al., 1984, and Ladeira et al., 1993, in gold extraction from cyanide solutions [31,34].

Despite the final overall Pt recovery results being very similar (also interpreted as achieving an equilibrium plateau), the conditions followed different kinetic rates during the first 6 h, with the lower Pt concentration (2 mg/L) achieving higher (and faster) recoveries. This performance suggests that, during the first 6 h of the test, the higher ratio of metal concentration to adsorption surface area allowed for a faster recovery at lower Pt concentrations. This interpretation is consistent with the higher K_2 constant obtained from the kinetic model at a 2 mg/L Pt concentration (Table 7), which showed a strong correlation with the pseudo-second-order model, with similar results between the experimental Q_e and the calculated Q_e .

3.2.5. Effect of Glycine

The effect of glycine (Gly) over Pt recovery was investigated. Tests were performed for 24 h at glycine concentrations of 1000, 3000, and 5000 mg/L. The results are presented in Figure 8 and Table 8.

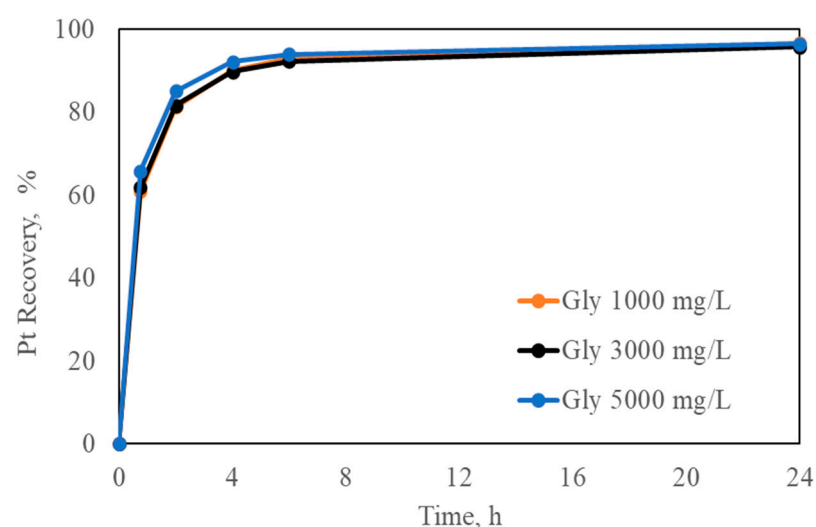


Figure 8. Effect of different initial Gly on Pt recovery (Pt-pure solution over carbon). Experimental conditions: Pt = 5 mg/L, [Gly] = 1000–3000–5000 mg/L, [CN] = 300 mg/L, pH = 10.5, carbon dosage = 10 g/L, and temperature = 24 °C.

Table 8. Kinetic model parameters determined at different glycine (Gly) concentrations.

Kinetic Model	Parameters	Gly (mg/L)		
		1000	3000	5000
Pseudo-first order	Q_e , Cal (mg/g)	0.15	0.14	0.12
	K_1 , (h^{-1})	1.40	0.18	0.13
	R^2	0.71	0.82	0.62
Pseudo-second order	Q_e , Exp (mg/g)	0.49	0.48	0.49
	Q_e , Cal (mg/g)	0.49	0.48	0.49
	K_2 , (g/mg×h)	6.89	7.82	9.48
	R^2	1.00	1.00	1.00

Figure 8 shows the adsorption kinetic and Pt recovery results for the different glycine concentrations tested. The similarity in the curves (achieving an equilibrium plateau) and

the overall Pt recovery obtained ($96.53\% \pm 0.38\%$, $95.72\% \pm 0.77\%$, and $96.41\% \pm 0.34\%$ at 1000 mg/L, 3000 mg/L, and 5000 mg/L, respectively), are suggesting that glycine concentrations do not have a significant impact over the final Pt recovery (under the tested conditions). This is consistent with the similarity of the K_2 constant calculated in the kinetic model at the different concentrations tested and the results obtained by Tauetsile et al., 2019, on gold recovery ($>99\%$) at different glycine concentrations (0 to 15 g/L) in the absence of copper [17].

Table 8 presents the parameters calculated for the kinetic model at different Gly concentrations. The results suggest a strong correlation with the pseudo-second-order model, with similar results between the experimental Q_e and the calculated Q_e .

3.2.6. Effect of Cyanide (CN)

The existing literature on gold adsorption suggests that the cyanide concentration has an important role in the loading rate and equilibrium capacity of gold adsorption [34].

The impact of different cyanide (CN) concentrations over Pt recovery was investigated. Multiple 24 h tests were performed at CN concentrations of 100, 300, and 500 mg/L. The curves contained in Figure 9 have been interpreted as achieving an equilibrium plateau in all the conditions tested, with Pt recoveries of $97.12\% \pm 0.18\%$, $95.72\% \pm 0.77\%$, and $96.10\% \pm 0.11\%$ at 100 mg/L, 300 mg/L, and 500 mg/L CN concentrations, respectively. These results are consistent with the K_2 constant calculated in the kinetic model at the different concentrations tested (Table 9). The rate of Pt adsorption was found to be poorly affected by the cyanide concentration, which could potentially be related to a competitive complexation between glycine and cyanide. At alkaline glycine–cyanide solutions, glycine forms strong complexes with Pt, stabilizing the metal species in the solution. This reduces the relative role of CN as the main complexing agent and even more cyanide is added; the speciation is already dominated by glycine–metal complexes. These results confirm the applicability of glycine, a more environmentally friendly product, and the reduction in CN in the hydrometallurgical process [35].

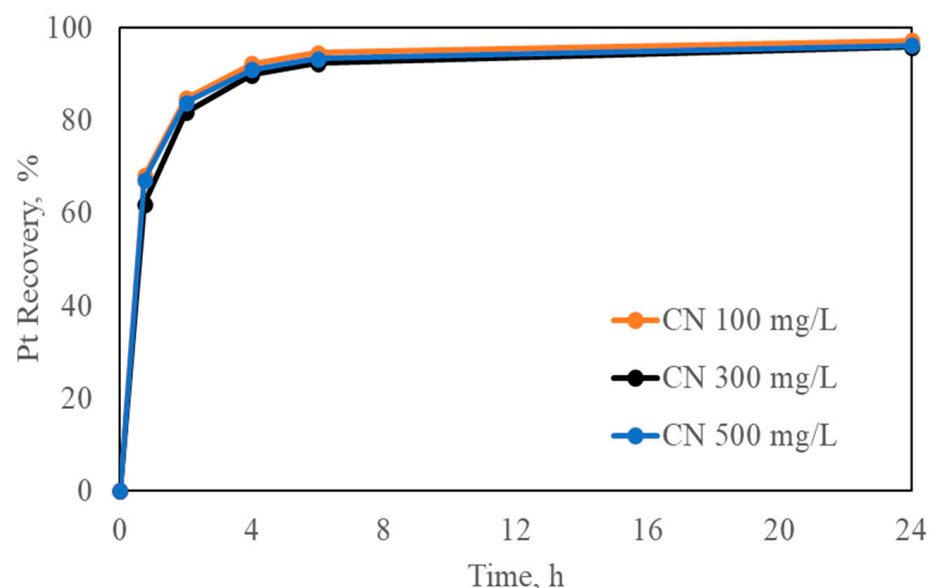


Figure 9. Effect of different initial CN concentrations on Pt recovery (Pt-pure solution over carbon). Experimental conditions: Pt = 5 mg/L, [CN] = 100–300–500 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 10 g/L, and temperature = 24 °C.

Table 9. Kinetic model parameters determined at different cyanide concentrations.

Kinetic Model	Parameters	Gly (mg/L)		
		1000	3000	5000
Pseudo-first order	Q_e , Cal (mg/g)	0.12	0.14	0.13
	K_1 , (h^{-1})	0.16	0.18	0.12
	R^2	0.72	0.82	0.63
Pseudo-second order	Q_e , Exp (mg/g)	0.49	0.48	0.49
	Q_e , Cal (mg/g)	0.49	0.48	0.48
	K_2 , (g/mg $\times$ h)	9.23	7.82	8.89
	R^2	0.99	0.99	0.99

Table 9 contains the parameters calculated for the kinetic model at different CN concentrations. The results suggest a strong correlation with the pseudo-second-order model, with similar values between the experimental Q_e and the calculated Q_e .

3.3. Isotherm Models

The isotherm Langmuir and Freundlich parameters calculated are shown in Table 10.

Table 10. Isotherm parameters for Pt adsorption at different initial Pt concentrations.

Langmuir Parameters					Freundlich Parameters		
[Pt] (mg/L), $t = 0$	K_L (L/mg)	R_L	Q_m (mg/g)	R^2	K_f (mg/g)/(mg/L) ^{1/n}	n	R^2
2	0.54	0.01	5.31	0.96	1.23	1.47	0.95
5	0.63	0.01	4.52	0.99	1.41	1.51	0.98
10	0.51	0.01	4.47	0.99	1.26	1.92	0.94

The experimental data from five different mass to volume ratios of carbon (0.5, 2, 5, 10, and 20 g/L), tested at three different initial concentrations of platinum (2, 5, and 10 mg/L Pt), fit slightly better with the Langmuir model ($R^2 > 0.96$), suggesting a probable monolayer adsorption process rather than multiple adsorptions (Figure 10). This is consistent with the results obtained by Fujiwara et al., 2007, on Pt, Pd, and Au from aqueous solutions onto L-lysine modified crosslinked chitosan resin [36].

Figure 10 shows that the different Pt concentrations tested followed a similar trend (slope) in the experimental adsorption isotherm. An increasing loading capacity can be observed with higher Pt concentrations in the solution, highlighting how the availability of metal in the solution enhances Pt adsorption onto the activated carbon.

According to the Langmuir model (Table 10), the maximum uptake capacity (Q_m) calculated at different initial Pt concentrations ranged from 4.47 mg/g to 5.31 mg/g with a correlation coefficient (R^2) > 0.96 .

This trend for Pt is consistent with the results achieved by Tauetsile et al., 2019, in gold, and Rubina et al., 2025, for palladium, who concluded that a higher initial metal concentration in the solution results in higher adsorption due to the increased availability of metal in the Gly-CN solution [17,20].

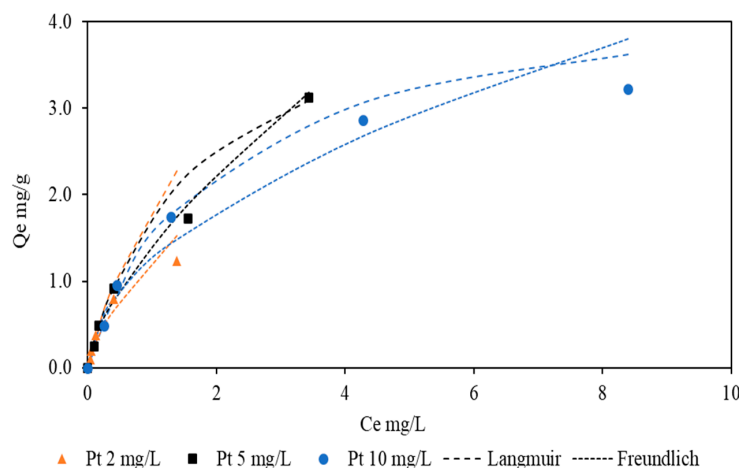


Figure 10. Equilibrium adsorption isotherm fitted with Langmuir isotherm at different initial platinum concentrations. Experimental conditions: [Gly] = 3000 mg/L [CN] = 300 mg/L, pH = 10.5, and temperature = 24 °C.

In general, based on the pseudo-second-order kinetics and the Langmuir isotherm, the adsorption mechanisms are likely to be governed by specific chemisorption at active surface sites. These mechanisms involving Pt glycine–cyanide complexes are consistent with the monolayer adsorption at homogeneous sites, as suggested by the Langmuir model.

3.4. Statistical Analysis: Significance of the Effect

3.4.1. ANOVA Analysis

Analysis of Variance (ANOVA) to the experimental data was performed using the software Design Expert, with the objective of determining the impact of the different sources of variability. The F-value compares the source’s mean square to the residual mean square, and the *p*-value refers to probability of obtaining the result achieved under the assumption that the null hypothesis H_0 is true (null hypothesis is significant if *p*-value is ≤ 0.05). Degrees of Freedom (df) is the number of estimated parameters used to compute the source’s sum of squares. Lack of Fit represents the amount where the model predictions miss the observations. R-squared (R^2) is a measure of the amount of variation around the mean explained by the model [32,33].

Table 11 shows the ANOVA assessment performed using the software Design Expert for a reduced quadratic model applied to Pt adsorption onto activated carbon data at the conditions tested in this research:

Table 11. Anova analysis of experimental data (kinetic test).

Source	Sum of Squares	df	Mean Square	F-Value	<i>p</i> -Value	
Model	4965.58	12	413.80	4633.54	<0.0001	Significant
Glycine	0.04	1	0.0367	0.41	0.52	Not significant
Cyanide	1.78	1	1.78	19.97	<0.0001	Significant
pH	35.18	1	35.18	393.96	<0.0001	Significant
Initial Pt conc.	1.06	1	1.06	11.82	0.0010	Significant
Carbon dosage	115.13	1	115.13	1289.15	<0.0001	Significant
Temperature	2603.27	1	2603.27	29,150.30	<0.0001	Significant
Residual	5.89	66	0.09			
Lack of fit	0.05	1	0.05	0.54	0.47	Not significant
Pure error	5.85	65	0.09			
R-squared						0.99

The Model F-value of 4633 implies that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

p-values (less than 0.05) indicate that the different conditions tested are significant model terms, except for glycine.

The Lack of Fit (F-value) of 0.54 implies that it is not significant relative to the pure error, indicating a good fit model.

The coefficient of correlation (R^2) value of 0.99 showed that the model equation was highly reliable.

3.4.2. Response Surface Methodology (RSM)

RSM is a collection of mathematical and statistical techniques that model the best fit of experimental data to a polynomial equation. RSM is useful for modeling, displaying, and analyzing different variables to understand processes and products [37].

Figure 11 shows the RSM results expressed as a contour plot (left) and 3D surface plot (right), illustrating the interaction between carbon dosage and temperature effects with fixed pH 9.5, Pt = 5 mg/L, Gly = 3000 mg/L, and CN = 300 mg/L. The model used a quadratic effect with two-factor interactions and indicates that the highest platinum adsorption efficiency occurs at ambient temperatures and higher carbon dosages.

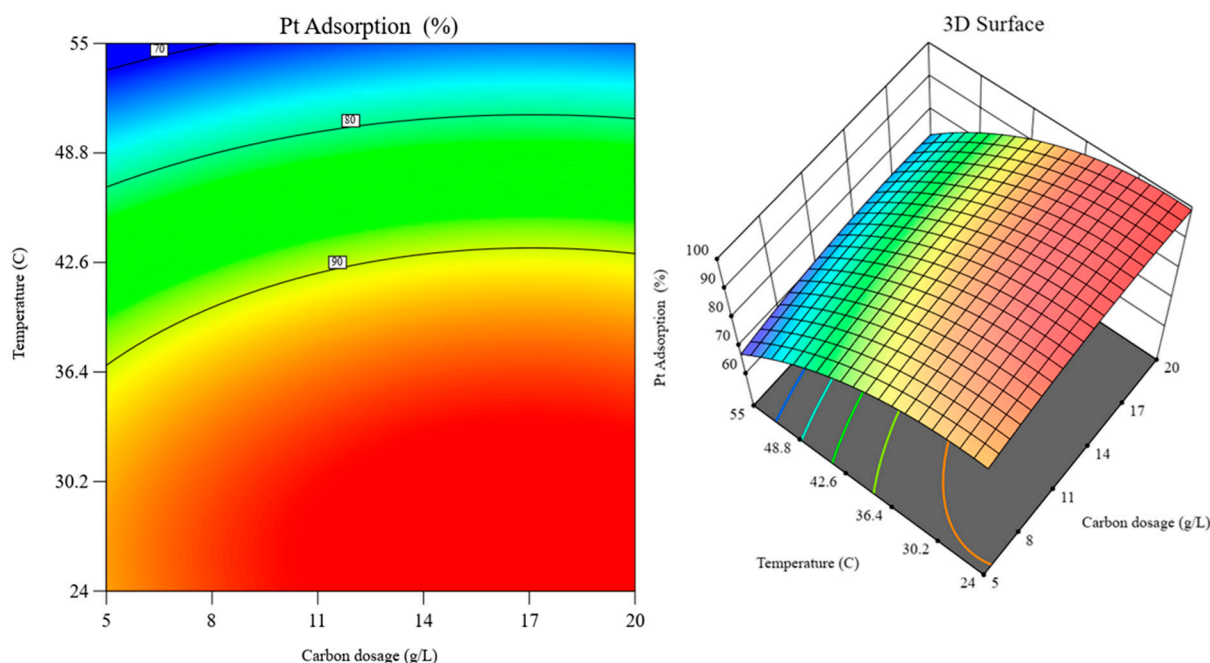


Figure 11. RSM graphs: contour plot (left) and 3D surface (right) over the interaction of carbon dosage and temperature effects (at fixed pH 9.5).

3.5. Complementary Test Results

Activated Carbon Selectivity in the Pt Adsorption

With the aim of assessing the adsorption selectivity of activated carbon in solutions with different metals (Pt, Pd, and Au), recovery tests were performed following standard conditions. Results (Figure 12) showed 95.9%, 98.1%, and 99.9% for Pt, Pd, and Au, respectively, confirming that Pt can be recovered from solutions in the presence of other precious metals. It shows that it follows similar kinetic behavior to the other precious metals despite Pd and Pt being less effectively adsorbed than Au in a polymetallic system. This result could be explained by the strong stability of the gold complexes in comparison with the corresponding Pd and Pt complexes and also coincides with the study performed by Chand et al., 2009, on hydrochloric acid [38]. Furthermore, the differences achieved in

recovery could be preliminarily considered as significant from a process design perspective due to the potential financial impact that different results can have on an industrial scale.

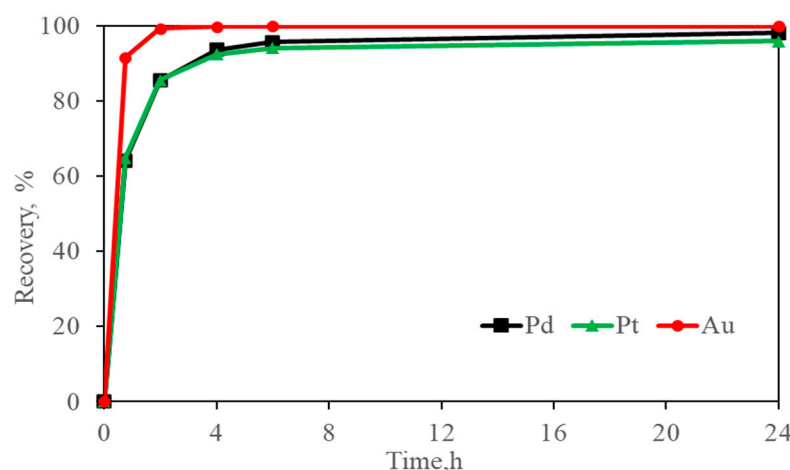


Figure 12. Platinum, palladium, and gold adsorption using activated carbon from Gly-CN solutions. Standard Conditions: Pt = 2.5 mg/L, Pd = 5 mg/L, Au = 5.5 mg/L, [CN] = 300 mg/L, [Gly] = 3000 mg/L, pH = 10.5, carbon dosage = 10 g/L, and ambient temperature (24 °C).

4. Conclusions

The results and findings from this research study are showing that platinum can be successfully recovered from synthetic alkaline glycine–cyanide solutions using activated carbon (Haycarb YAO 60) in 24 h tests (92.3% recovery in standard conditions). Such solutions can derive from glycine leaching e-waste or catalytic converter waste, but the system was simplified to focus on platinum. Results are demonstrating that platinum can be successfully recovered under the effects tested: 92.37–97.93% (carbon dosage), 70.00–95.72% (temperature), 94.08–97.39% (pH), 95.16–96.23% (platinum concentration), 95.72–96.53% (glycine concentration), and 95.72–97.12% (cyanide concentration), with carbon dosage, pH, and temperature effects having the greatest impact (variability) over the adsorption results. In terms of the kinetic model, tests performed showed high correlations with a pseudo-second-order model, with similar results between the experimental Q_e and the calculated Q_e . Regarding the isotherm model, the experimental data fitted well ($R^2 > 0.9$) with the Langmuir model (assuming a monolayer adsorption), where the maximum uptake capacity (Q_m) at different initial Pt concentrations ranged from 4.47 mg/g to 5.31 mg/g. Complementary results have shown that Pt can also be recovered (95.9%) from glycine-starved CN solutions in the presence of other precious metals (palladium and gold in this study).

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Conflicts of Interest: The authors hereby declare that they have no conflicts of interest. Even though Messrs Eksteen and Oraby were the original inventors of the alkaline glycine leach and processing technology and its various variants, all intellectual property rights have been ceded to Curtin University and eventually acquired by Draslovka s.a. in 2022.

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