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Comparative Evaluation of Strong Base Anion Exchange Resin and Activated Carbon for Gold Cyanide Recovery Using Isotherm Modelling

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ABSTRACT

This study presents a comparative evaluation of strong base anion (SBA) exchange resin and activated carbon (AC) for the adsorption of gold cyanide complex ions, $Au(CN)_2^-$, from cyanide leach solutions. Batch adsorption experiments were conducted at varying dosages, and the equilibrium data were analysed using non-linear Langmuir, Freundlich, and Sips isotherm models. The SBA resin exhibited a significantly higher maximum adsorption capacity and stronger binding affinity (q_m=68.94mg/g, K_s=3.16 L/mg) than activated carbon (q_m= 34.11mg/g, K_s= 0.18 L/mg). Model fitting revealed that the Langmuir and Sips models best described the SBA resin's adsorption behaviour (R^2 = 0.9673, RMSE = 3.49), suggesting monolayer adsorption on a homogeneous surface. In contrast, activated carbon exhibited lower adsorption performance, characterised by greater surface heterogeneity (n = 0.92), as indicated by the Sips model (R^2 = 0.9427, RMSE = 2.07). These findings confirm that SBA resin provides superior adsorption efficiency, selectivity, and surface uniformity, making it a more promising material for gold recovery, especially in low-concentration or complex cyanide leach systems, compared to activated carbon

Keywords: gold; adsorption; sba resin; activated carbon; isothermal

1. Introduction

Since 1980, activated carbon has traditionally been the dominant adsorbent for modern gold recovery from cyanide leach solutions in carbon-in-pulp (CIP) and carbon-in-leach (CIL) [1]. This is attributed to its high surface area (e.g. macropores, mesopores and micropores), physical robustness, and economic viability. However, it does present certain limitations, including reduced selectivity, surface fouling, and degradation upon gold elution and the subsequent regeneration process [2]. In recent years, strong base anion (SBA) Ion Exchange (IX) resins have emerged as promising alternatives to activated carbon for recovering gold from cyanide solution. These resins exhibit a quaternary functional group that confers a competitive selectivity toward cyanide gold complex ion, $Au(CN)_2^-$ [3] and they maintain stable adsorption performance across a wide range of concentrations [4]. These benefits make resins the adsorbent of choice for challenging applications such as complex ore processing and low-grade leach solution treatment, where activated carbon may fall short. Fig. 1 illustrates the structural characteristics of both adsorbents. Activated carbon in Fig. 1(a) features a porous architecture comprising macropores, mesopores, and micropores, which provides a high surface area for adsorption. In contrast, the SBA resin in Fig. 1(b) is a cross-linked polymer matrix containing fixed functional groups that specifically target anionic gold complexes.

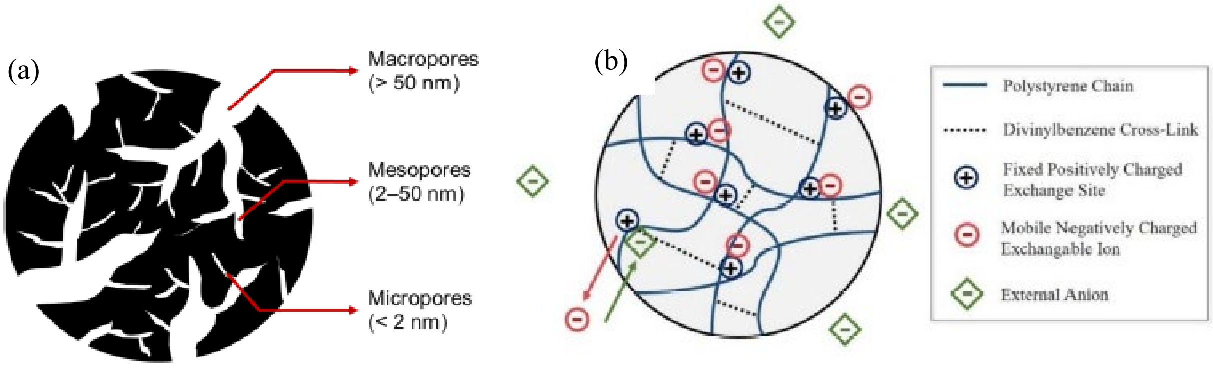

Fig. 1: Schematic diagram (a) activated carbon [2], and (b) SBA Resin [5]

Isotherm modelling is commonly employed to understand and quantify the adsorption mechanisms of these materials. This approach provides critical insights into adsorption capacities, surface interactions, and physicochemical behaviour. Due to their experimental simplicity and precise control over variables, batch adsorption studies are widely used to generate equilibrium data necessary for such modelling [6]. Batch systems are commonly used for such studies due to their operational simplicity, precise control over experimental variables, and ability to generate equilibrium data essential for model fitting [7]. Three widely applied isothermal adsorption models have been selected, e.g. Langmuir Isothermal Equilibrium model, Freundlich Isothermal Equilibrium model and Sip Isothermal Equilibrium model. These models provide critical insights into the adsorption behaviour, surface heterogeneity, and binding affinities [8] of $Au(CN)_2^-$ onto SBA resin and activated carbon under controlled batch conditions. The Langmuir isotherm model assumes monolayer adsorption on a structurally homogeneous surface, where each adsorption site has equal energy and no interaction occurs between adsorbed molecules [9]. The Freundlich model, on the other hand, describes adsorption on heterogeneous surfaces with varying affinities and allows for multilayer adsorption, making it appropriate for materials like activated carbon [10]. The Sips model integrates Langmuir and Freundlich assumptions, enabling it to represent adsorption on surfaces that exhibit homogeneity and heterogeneity in binding site energy distribution [9][11]. Fig. 2 illustrates these adsorption mechanisms. Fig. 2(a) shows monolayer adsorption, consistent with the Langmuir model, where a uniform layer of adsorbate forms over the adsorbent surface. Fig. 2(b) depicts multilayer adsorption, as proposed in the Freundlich model, which occurs on surfaces with non-uniform energy sites, allowing additional layers to form as adsorption progresses. Understanding these mechanisms is crucial in selecting the appropriate adsorbent for gold recovery from cyanide leach solutions and optimising adsorption system design [12]

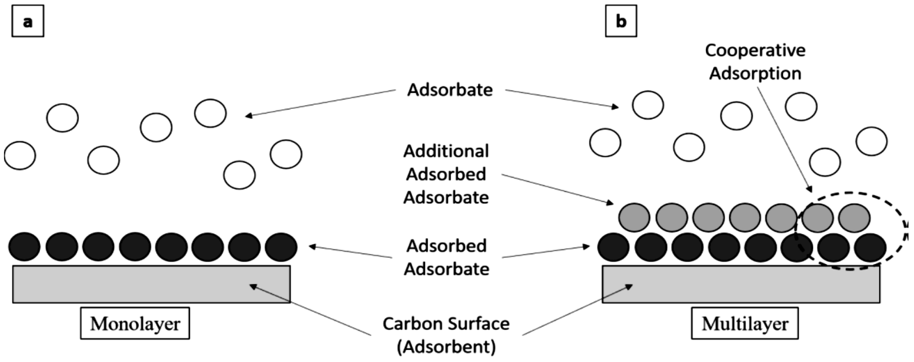

Fig. 2: Schematic (a) monolayer, and (b) multilayer of adsorbate onto carbon [12]

Considering the growing need for more efficient and selective materials for gold recovery, this study aims to comparatively evaluate the adsorption behaviour of activated carbon and strong base anion (SBA) ion exchange resin toward gold cyanide complexes. By applying non-linear isotherm models, namely, the Langmuir, Freundlich, and Sips models under controlled batch conditions, the study aims to elucidate the adsorption mechanisms, quantify adsorption capacities, and assess surface affinities. The resulting insights are expected to guide the selection of optimal adsorbents for cyanide leach systems, particularly in low-grade or complex ore environments where conventional activated carbon may be insufficient.

2. Materials and Methods

2.1 Materials and Chemicals

The isothermal batch adsorption experiments were conducted using two different types of adsorbents. The first adsorbent, activated carbon, was procured from RS Marketing Resources Sdn. Bhd in Johor Bharu, Malaysia. It exhibited a particle size distribution ranging from 3.35 mm to 1.7 [6x12 mesh] with over 90% passing, and a bulk density of 0.54 g/mL. The second adsorbent was a Type 1 Strong Base Anion (SBA) ion exchange (IX) resin, (ESA 304) ordered from East Chemical Science Tech Co. Ltd, Shenyang. China. ESA 304 is a porous gel structure of copolymer of styrene and DVB functionalised with a quaternary ammonium group in the ionic form of Chloride (Cl^-). The particle size distribution of the resin ranged from 0.315 to 1.25mm, [50-16 mesh], with over 95% passing, and the density is 1.06g/mL. Both adsorbents' physical characteristics have been verified by ASTM standards (D2862, D2854 and D2187). The adsorbate medium used in this experiment was a 1000 ppm Gold (Au) in cyanide solution (0.3% w/v) NaCN ordered from Inorganic Ventures (IV) (United States). Additional chemicals used included standard-grade 1000 ppm sodium cyanide (NaCN) solid powder, analytical-grade silver nitrate ($AgNO_3$) crystal powder, and sodium hydroxide (NaOH) pellets, all supplied by Sigma-Aldrich.

2.2 Material and Experiment Preparation

2.2.1 SBA pretreatment procedure

Before use, the SBA resin was pretreated to ensure optimal adsorption performance. The resin was first soaked in deionised water for 2–4 hours, followed by a thorough rinse. A 20–30 cm layer of water was maintained above the resin bed throughout the procedure to prevent drying. Next, the resin was washed with a 4% hydrochloric acid (HCl) solution, followed by rinsing with deionised water until the effluent pH reached 4 or higher. An alkali wash using a 4% sodium hydroxide (NaOH) solution was subsequently performed, followed by rinsing until the effluent pH reached 10 or lower. A second acid wash with 4% HCl was then conducted, and the resin was rinsed again with deionised water until the pH stabilised at four or higher. The treated resin was stored with a 20–30 cm layer of water above the bed to maintain hydration until use.

2.2.2 Activated carbon pretreatment procedure

The activated carbon was pretreated before use to remove surface impurities and ensure consistent physicochemical properties. The carbon was first thoroughly rinsed with deionised water to remove fine particles, dust, and residual manufacturing contaminants. Washing was continued until the rinse water appeared clear. The carbon was soaked in a dilute hydrochloric acid (HCl) solution (typically 1–4%) for several hours to remove soluble inorganic impurities, such as metal ions or ash content that may interfere with adsorption. After acid treatment, the carbon was rinsed repeatedly with deionised water until the effluent reached a near-neutral pH (6–7). Once clean, the activated carbon was dried in an oven at 105 °C for a minimum of 12 hours to remove all moisture. The dried carbon was then cooled in a desiccator to prevent moisture reabsorption from the atmosphere and stored in an airtight container until use in batch adsorption tests.

2.2.3 Gold cyanide solution preparation and assay analysis

A 250 mL gold cyanide solution was prepared at a pH range of 10–11, containing 600 ppm of cyanide (CN^-), and used to evaluate the adsorption performance of different adsorbent dosages. All batch adsorption experiments were conducted in triplicate under standardised experimental conditions to ensure reproducibility. The cyanide concentration in each solution was determined via argentometric titration using 0.0103 M silver nitrate ($AgNO_3$) with rhodamine B as the indicator of the endpoint. The solution pH was monitored using a calibrated pH meter. Batch adsorption experiments were conducted using an automatic orbital shaker set at 300 rpm and maintained at 30 °C. At predetermined intervals, 1 mL aliquots were withdrawn from each sample using a pipette and transferred into 10 mL test tubes. Each aliquot was then diluted with 9 mL of deionised (DI) water to ensure an appropriate detection range prior to gold concentration analysis using inductively coupled plasma optical emission spectrometry (ICP-OES).

2.2.4 Adsorption isothermal equilibrium study

Table 1 presents a summary of the three non-linear adsorption isotherm models used to evaluate the gold adsorption performance of each resin and activated carbon dosage

Table 1: Summary of nonlinear adsorption isotherm models, equations, and parameters

Model	Nonlinear Equation	Parameter	References
Langmuir Isothermal Equilibrium	$q_e = \frac{q_m K_L C_e}{1 + K_L C_e}$	q_e = Equilibrium adsorption capacity (mg/g) C_e = Equilibrium concentration of adsorbate in the solution (mg/L) K_L = Langmuir constant (L/mg) q_m = Maximum adsorption capacity (mg/g)	[8][12]
Freundlich Isothermal Equilibrium	$q_e = K_f C_e^{\frac{1}{n}}$	q_e = Equilibrium adsorption capacity (mg/g) C_e = Equilibrium concentration of adsorbate in the solution (mg/L) K_f =Freundlich constant $[(mg.g^{-1})/(mg.L^{-1})^n]$ n = Heterogeneity factor	[12][13]
Sip Isothermal Equilibrium	$q_e = \frac{q_m (K_s C_e)^n}{1 + (K_s C_e)^n}$	q_e = Equilibrium adsorption capacity (mg/g) C_e = Equilibrium concentration of adsorbate in the solution (mg/L) Ks = Sip constant (L/mg) q_m = Maximum adsorption capacity (mg/g) n = Heterogeneity factor	[9][14]

Corresponding adsorption equilibrium graphs will be plotted and compared to assess the applicability of each model. To determine the best-fitting model, error analysis will be conducted using statistical indicators including the coefficient of determination (R^2), root mean square error (RMSE), and Akaike Information Criterion (AIC). These metrics will provide quantitative support for model selection by assessing both goodness-of-fit and model complexity.

Table 1: Error functions as an isotherm model fitting selection criterion

Error Function	Formula	References
Coefficient of Determination (R^2)	$R^2 = 1 - \frac{\sum_{i=1}^{N}(q_{exp} - q_{model})^2}{\sum_{i=1}^{N}(q_{exp} - q_{mean})^2}$	[15]
Root Mean Square Error (RMSE)	$RMSE = \sqrt{MSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(q_{exp} - q_{model})^2}$	[15]
Akaike Information Criterion (AIC)	$AIC = N.Ln\left(\frac{1}{N}\sum_{i=1}^{N}(q_{exp} - q_{model})^2\right) + 2.K$ $where\ N = No\ of\ samples$ $where\ K = Number\ of\ parameter$	[16]

3. Results and Discussion

3.1 Strong Base Anion (IX) Resin (ESA 304)

The adsorption equilibrium data for the gold cyanide complex ion, $Au(CN)_2^-$, onto strong base anion (SBA) resin were analysed using three non-linear isotherm models (e.g., Freundlich, Langmuir, and Sips). These models explain the relationship between the equilibrium amount of $Au(CN)_2^-$ adsorbed on the resin (qe) and the equilibrium concentration of $Au(CN)_2^-$ in the liquid phase (Ce). Furthermore, they provide insight into the adsorption mechanism, surface characteristics, and binding affinity between the resin and the $Au(CN)_2^-$.

The Freundlich isotherm accounts for multilayer adsorption and surface heterogeneity. The Freundlich heterogeneity factor n is 2.24, where $0 < 1/n < 1$, indicating favourable adsorption and a high affinity. While the model captured the general trend, it slightly overpredicted the adsorption capacity compared to experimental values. Statistically, the Freundlich model showed the lowest coefficient of determination, R^2 (0.9291), the highest root mean square error, RMSE (5.14), and the highest Akaike information criterion, AIC (26.92) among the three models. These results suggest that multilayer formation or strong surface heterogeneity is not the dominant mechanism for gold cyanide adsorption on resin under the studied batch conditions.

In contrast, the R^2 (0.9672) in the Langmuir isotherm model is higher than that of the Freundlich model. Furthermore, low RMSE (3.49) and the lowest AIC (21.51) indicate that adsorption of $Au(CN)_2^-$ occurs at specific homogeneous sites within the resin, forming a monolayer. The Langmuir equilibrium constant, $KL = 3.09$ L/mg, reflects a high binding affinity, illustrating the strong thermodynamic tendency for $Au(CN)_2^-$ to adsorb onto the resin matrix. The Langmuir separation factor (RL) ranged from 0.01 to 0.03, which falls within the range ($0 < RL < 1$) that explains the adsorption process is favourable [12]. Such a low RL ($RL \approx 0$), which is almost irreversible, suggests a strong affinity, as confirmed by the KL value.

The Sips isotherm model, a combination of the Langmuir and the Freundlich models, showed comparable performance. The R^2 (0.9673) and RMSE (3.49) values are almost similar to those of the Langmuir model, which shows a similar degree of goodness of fit. However, the AIC (23.50) for the Sip model is slightly higher, suggesting a marginally less efficient model in terms of complexity versus fit quality. The $n = 1.02$ is very close to 1, implying that the adsorption surface exhibits near-homogeneous characteristics with uniform binding affinities, similar to the Langmuir assumption [14]. The converted Sip constant Ks(1/n) value is 3.10 L/mg, which is almost identical to KL = 3.10 L/mg, supporting the hypothesis that monolayer chemisorption occurs on a structurally homogeneous resin surface. Table 3, 4 and Fig. 3 below show the assay result for the batch experiment and the comparison graph of gold cyanide adsorption onto SBA(IX) resin, analysed using three non-linear isotherm models and their corresponding error parameters.

Table 2: Assay result analysis for resin

Dose (g/L) (Resin)	Co (mg/L)	Ce at Equilibrium time (mg/L)	qe experiment) (mg/g)
0.5	33.00	2.40	61.19
1.0	33.00	0.29	32.71
2.0	33.00	0.06	16.47
3.0	33.00	0.05	10.98
4.0	35.36	0.06	8.83
4.0	19.76	0.06	4.93
4.0	10.19	0.02	2.54

Table 3: Non-linear isothermal models' data of SBA (IX) Resin

Model	**Non-Linear Freundlich Isothermal Model**	**Non-linear Langmuir Isothermal Model**	**Non-Linear Sip Isothermal Model**
Parameter	K_f: 42.43	q_{max} (mg/g): 69.53	q_{max} (mg/g): 68.94
		K_L (L/mg): 3.07	K_S(L/mg)): 3.16
	n: 2.24	R_L Max: 0.03	n: 1.02
		R_L Min: 0.01	
R²:	0.9291	0.9672	0.9673
RMSE:	5.14	3.49	3.49
AIC:	26.92	21.51	23.50

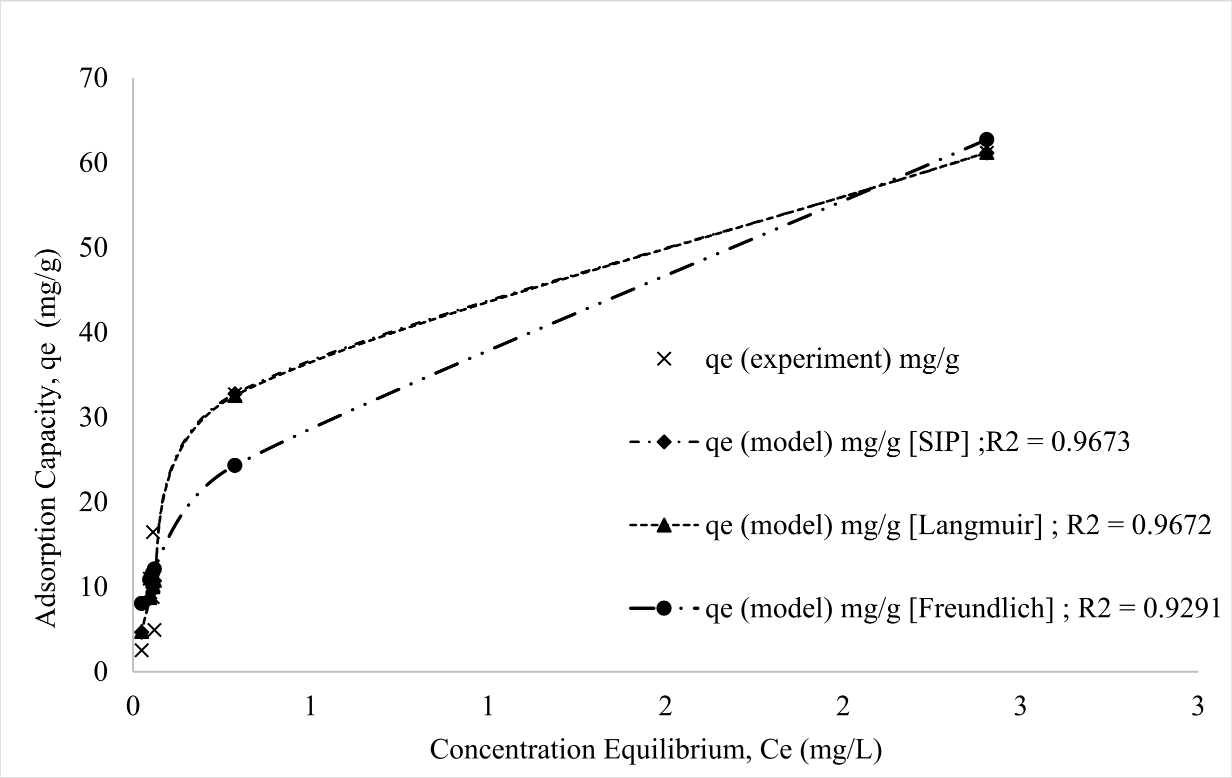

Fig. 3: Non-linear adsorption equilibrium isothermal of SBA (IX) Resin

3.2 Activated carbon

The adsorption equilibrium data for gold cyanide complex ion, $Au(CN)_2^-$, onto activated carbon were analysed using three non-linear isotherm models (e.g., Freundlich, Langmuir, and Sips). These models explain the relationship between the equilibrium amount of $Au(CN)_2^-$ adsorbed on the activated carbon (qe) and the equilibrium concentration of $Au(CN)_2^-$ in the liquid phase (Ce). Furthermore, they provide insight into the adsorption mechanism, surface characteristics, and binding affinity between the activated carbon and the $Au(CN)_2^-$.

The Freundlich isotherm accounts for multilayer adsorption and surface heterogeneity. The Freundlich heterogeneity factor n is 2.43, where $0 < 1/n < 1$, indicating favourable adsorption and a high affinity. While the model captured the general trend, it slightly overpredicted the adsorption capacity compared to experimental values. Statistically, the Freundlich model showed the lowest coefficient of determination, R^2 (0.9083), the highest RMSE (2.62), and the AIC (17.49), among the three models. These results suggest that multilayer formation or strong surface heterogeneity is not the dominant mechanism for gold cyanide adsorption on activated carbon under the studied batch conditions.

In contrast, the R^2 (0.9423) in the Langmuir isotherm model is higher than that of the Freundlich model. Furthermore, low RMSE (2.08) and the lowest AIC (14.24) indicate that adsorption of $Au(CN)_2^-$ occurs at specific homogeneous sites within the resin, forming a monolayer. Langmuir equilibrium constant $K_L = 0.21$ L/mg reflects a low binding affinity, illustrating the weak thermodynamic tendency of $Au(CN)_2^-$ to adsorb onto the activated carbon surface compared to ion exchange resin. This is likely due to the physical nature of physisorption and the weaker specific interaction between the adsorbate and the activated carbon surface. The Langmuir separation factor (R_L) ranged from 0.12 to 0.32, which falls within the range ($0 < R_L < 1$) that explains the adsorption process is favourable.

The Sips isotherm model, a combination of the Langmuir and the Freundlich models, showed comparable performance. The R^2 (0.9427) and RMSE (2.07) values are almost similar to those of the Langmuir model, which shows a similar degree of goodness of fit. However, the AIC (16.19) for the Sip model is slightly higher, suggesting a marginally less efficient model in terms of complexity versus fit quality. The $n = 0.92$ is less than 1 ($n < 1$), reflecting surface heterogeneity, which aligns with the Freundlich model in representing non-linear adsorption and a distribution of adsorption energies across the resin surface. The converted Sip constant $K_s{}^{(1/n)}$ value is 0.195 L/mg, which is very close to $K_L = 0.21$ L/mg, further indicating that while the adsorption follows monolayer characteristics, the activated carbon surface possesses a degree of heterogeneity. Table 5, 6 and Fig. 4 show the assay result for the batch experiment and the comparison graph of gold cyanide adsorption onto activated carbon, analysed using three non-linear isotherm models and their corresponding error parameters.

Table 4: Assay result analysis for activated carbon

Dose (g/L) (Activated Carbon)	**Co (mg/L)**	**Ce at Equilibrium time (mg/L)**	**qe experiment) (mg/g)**
0.5	36	23.33	25.34
1.0	36	10.15	25.85
2.0	36	5.26	15.37
3.0	36	2.85	11.05
4.0	35.36	1.93	8.36
4.0	19.76	0.34	4.85
4.0	10.19	0.20	2.50

Table 5: Non-linear isothermal models of activated carbon (AC)

Model	**Non-Linear Freundlich Isothermal Model**	**Non-linear Langmuir Isothermal Model**	**Non-Linear Sip Isothermal Model**
Parameter	K_f: 7.74	q_{max} (mg/g): 32.57	q_{max} (mg/g): 34.11
		K_L (L/mg): 0.21	K_S(L/mg)): 0.18
	n: 2.43	R_L Max: 0.32	n: 0.92
		R_L Min: 0.12	
R^2:	0.9083	0.9423	0.9427
RMSE:	2.62	2.08	2.07
AIC:	17.49	14.24	16.19

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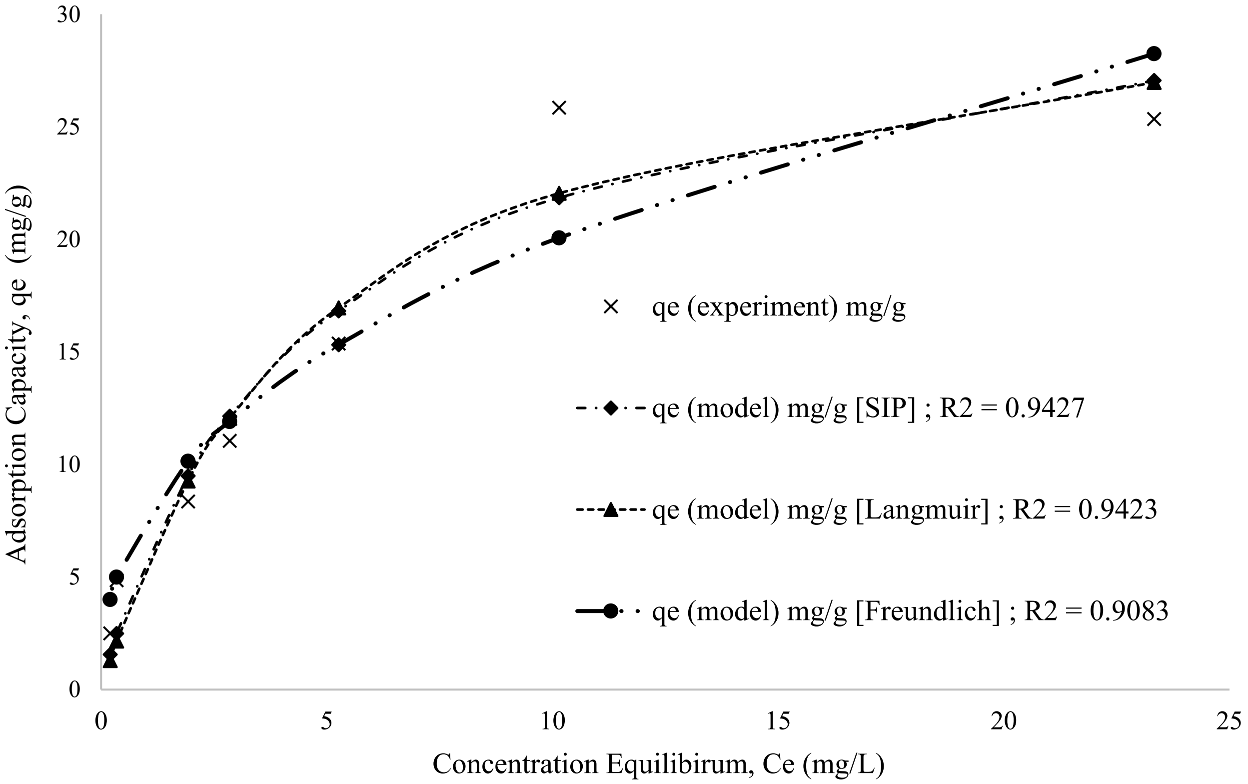

Fig. 4 : Non-linear isothermal of activated carbon

3.3 Discussion

The maximum adsorption capacity (q_{max}) represents the theoretical upper limit of an adsorbent's ability to retain gold cyanide ions $Au(CN)_2^-$ per unit mass. In this study, the SBA resin exhibited a significantly higher maximum adsorption capacity (q_{max} = 68.94 mg/g) than activated carbon (q_{max} = 34.11 mg/g), indicating its superior adsorption capacity. This suggests that SBA resin can take higher concentrations of $Au(CN)_2^-$ without reaching saturation, allowing for sustained adsorption performance with minimal adsorbent dosage. In contrast, the lower q_{max} of activated carbon makes it prone to rapid saturation, necessitating higher amounts of activated carbon to achieve comparable gold recovery.

The affinity constant, Ks (L/mg), derived from the Sips model, reflects the binding strength, selectivity and adsorption efficiency between the adsorbent and the adsorbate. The SBA resin demonstrates a higher affinity constant (Ks = 3.16 L/mg) than AC (Ks = 0.18 L/mg), indicating a much stronger binding affinity for $Au(CN)_2^-$. This high affinity makes the resin more selective, with high specificity toward $Au(CN)_2^-$ due to positively charged quaternary groups that electrostatically attract anionic gold complexes. In contrast, the lower Ks value in AC reflects weaker, less specific interactions, possibly involving van der Waals forces, π–π interactions, or hydrogen bonding. These interactions make it less selective in systems with multiple competing anions. A high Ks affects the adsorption efficiency, especially at lower concentrations, for example, in tailing, where traces of $Au(CN)_2^-$ can effectively be recovered. Conversely, activated carbon may exhibit lower removal efficiency under such dilute conditions, resulting in earlier breakthrough and reduced adsorption performance.

The heterogeneity factor (n) in the Sips isotherm model reflects the uniformity of adsorption site energies and the extent of monolayer formation on the adsorbent surface. The strong base anion (SBA) resin exhibited an n value of 1.02, indicating a predominantly homogeneous surface where the active sites possess similar affinities toward the $Au(CN)_2^-$. This uniformity facilitates consistent and predictable adsorption interactions. Meanwhile, activated carbon showed a lower n value of 0.9206, consisting of a heterogeneous surface. This suggests the presence of adsorption sites with diverse energy profiles, leading to variable binding affinities and less uniform adsorption behaviour.

Although the Langmuir model provided a good fit and mechanistically explains monolayer adsorption, the Sips model offered a statistically superior fit with greater flexibility in accounting for surface heterogeneity, particularly for activated carbon. Its dual-character nature allows it to describe both uniform and non-uniform adsorption behaviours in a single model. This was especially useful in comparing SBA resin and activated carbon, where one exhibits near-homogeneous site energies (SBA resin, n = 1.02) and the other displays variable surface properties (AC n = 0.92). Moreover, the Sips constant (Ks) and the maximum adsorption capacity (q_{max}) not only reflect the statistical quality of the model fit but also correlate well with the known physicochemical characteristics of the materials. Therefore, the Sips isotherm was selected as the most appropriate model to describe the equilibrium behaviour of gold cyanide adsorption onto both adsorbents under the studied batch conditions.

Table 6: Result comparison between three isothermal models on SBA Resin vs Activated Carbon

Model	Parameter		S.B.A (IX) Resin	Activated Carbon
Sip Isothermal Model	Maximum Adsorption Capacity	q_{max} (mg/g):	68.94	34.11
	Affinity of binding sites	K_S (L/mg):	3.16	0.18
	Heterogeneity Factor	n:	1.02	0.92
Langmuir Isothermal Model	Maximum Adsorption Capacity	q_{max} (mg/g):	69.53	32.58
	Affinity of binding sites	K_L (L/mg):	3.07	0.21
	Adsorption Favourability (Separation factor)	$R_{L(minimum)}$:	0.01	0.12
		RL $_{(maximum)}$:	0.03	0.32
Freundlich Isothermal Model	Freundlich constant	K_S (L/mg)):	42.43	7.74
	Adsorption Intensity	n:	2.24	2.43

4. Conclusion

The adsorption performance of strong base anion (SBA) resin and activated carbon for gold cyanide complex, $Au(CN)_2^-$, was comprehensively evaluated using non-linear Freundlich, Langmuir, and Sips isotherm models. SBA resin exhibited a markedly higher maximum adsorption capacity (q_{max} = 68.94 mg/g) and stronger binding affinity (K_s = 3.16 L/mg) than activated carbon (q_{max} = 34.11 mg/g; K_s = 0.18 L/mg), indicating its superior capacity and selectivity toward $Au(CN)_2^-$ ions. The Sips model provided the best overall fit for both materials, offering the flexibility to account for heterogeneous (AC) and near-homogeneous (SBA resin) surface energy distributions. For SBA resin, the Sips heterogeneity factor (n) is almost 1, suggesting monolayer adsorption on nearly uniform binding sites, consistent with the Langmuir model's assumptions. Activated carbon, on the other hand, exhibited a more heterogeneous surface (n = 0.92), lower affinity, and reduced adsorption capacity, leading to earlier saturation and lower efficiency. Therefore, the Sips isotherm was deemed most suitable for describing the equilibrium behaviour of both materials, with SBA resin outperforming activated carbon in terms of capacity, affinity, and site uniformity, making it the more effective adsorbent for gold recovery from cyanide leachates, particularly in low-concentration or complex systems.

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