

Adsorption Behavior of Copper and Paracetamol Residues in Removal Strategy from Hospital Wastewater on Beninese Kaolinite Surface

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Abstract Heavy metal and drug residues in the environment have become serious pollutants to be addressed. Grey waters from municipalities, hospitals and chemical industries may be loaded with these chemicals and end up into the environment, especially in water springs, rivers and lakes. Moreover, the pre-treatment measures for these wastewaters are needed to ensure the treated water is environmentally safe and unpolluted. Therefore, we aimed in this work to optimize the physicochemical conditions that favour their adsorption onto Beninese Kaolinite geopolymer from Ketou. Moreover, a quantum chemical mechanistic modeling showed that the adsorption of copper and paracetamol is exothermic according to a single mode for copper with an energy of $-139.15 \text{ kJ.mol}^{-1}$ while that of paracetamol is in two modes, namely the horizontal mode having a high energy of $-159.40 \text{ kJ.mol}^{-1}$, and the vertical mode of $-91.10 \text{ kJ.mol}^{-1}$. By heating the kaolinite that had adsorbed these pollutants, it can release them at 435 K and 750 K respectively. Under these conditions, the geopolymer eliminates about 90% of the Cu^{2+} ions and 72% of the paracetamol. This adsorption process does not cause any disorder in its structure ($\Delta S < 0$), as follow the Pseudo-second order model with $R^2 > 0.99$ and its isotherms are well simulated by Langmuir model. Application to hospital wastewater gave reduction rates in copper of $90.5 \pm 2.1\%$ and in paracetamol of $88.5 \pm 3.65\%$. Kaolinite was found to be an effective adsorbent for treating industrial wastewater before its discharge into the environment.

Keywords: Adsorption, Kaolinite, Copper, Paracetamol, Wastewater

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1. Introduction

Numerous clay deposits in Benin can be exploited for industrial water purification. These clay minerals are often used in pottery, in the construction of adobe walls and in the industrial manufacture of bricks [1]. Kaolinite predominates in the commune of Ketou, located in the Plateau Department. The geopolymer developed by Dazogbo et al. [2], from Kaolinite collected in the same commune showed maximum absorption of Methyl Blue at pH 4.2 with an adsorption yield of 80%. Based on the results of the elimination of organic dyes (methyl blue) by geopolymers manufactured from kaolinite, we were

motivated to study their capacities to eliminate Trace Metal Elements (TME) and Drugs Residues (DR) products as well as the analytical conditions that enable to obtain the best yields (optimization) and validate the optimised protocol through its application to the industrial wastewater treatment. Furthermore, there are several sources of TME and DR in these environments, but liquid discharges are the main source with industry being the major contributor [3]. As some authors have pointed out, industrial wastewater in Benin ends up in the sea or in freshwater bodies [4] although some factories such as Beninese Company for Industrial Transformations have some wastewater treatment plants and yet industrialisation has developed considerably in the case of the textile industry, metallurgical and chemical industries

respectively. Water resources pollution by TME in Benin is already a reality and found that water from wells and boreholes used to water crops at the Houeyiho market garden site in Cotonou was contaminated with Cd, Pb and Mn [5]. The levels of heavy metals in fish products from Lake Nokoue exceed the tolerated threshold for lead and copper for fish and shrimp samples (2.85 mg/kg) [4]. Among the pharmaceutical products on the Beninese market such as aspirin residues, paracetamol, ibuprofen, diazepam, diclofenac and carbamazepine are the most commonly found in environmental matrix [6]. In the aquatic environment, these risks can lead to sex reversal of fish males [7], kidney damage and altered gills caused by diclofenac [8], neuroteratogenic effects for humans, cancer and many other diseases. Under these conditions, prevention is the only efficient way to limit the consequences of the degradation of water resources and to preserve the environment through treatment.

Although, there are several widely adopted wastewater treatment methods (e.g. reverse osmosis, electrochemical treatment, adsorption), the most effective way of limiting contamination of water resources involves the development of an adsorption technique [9,10]. Moreover, clays are promising alternative and are of great interest in the elimination of heavy metals from wastewater. Since adsorption is a function of several parameters (pH, temperature, particle size, mass ratio, initial concentration, stirring speed, etc.) and the yield varies according to the variation in one or the other parameter, it becomes necessary to determine the operating conditions of the method using an optimization approach in order to make it more cost-effective and applicable.

This study aims to optimise the fixation of TME and DR

on kaolinite in order to improve the method applicability by increasing the adsorption yield. More specifically, we have theoretically determined the adsorption mechanisms of copper and paracetamol on Kaolinite crystalline surface by Quantum Chemical Strategies from VASP software and experimentally from optimal parameters, kinetic and isotherm models for the adsorption of TME and DR onto the kaolinite-based geopolymer.

2. Material and Methods

2.1. Sample Site Collection

The geopolymer used as an adsorbent was developed by Dazogbo from Kaolinite collected with Ferdinand Goudjo in the commune of Ketou in Benin. The industrial wastewater samples were collected at CHU-MEL (University Hospital Center of Mother and Child Lagoon) located at Cotonou in Benin. The technique recommended by APHA *et al.* [11] was used for wastewater sampling. Using the AQUARED brand multiparametric probe, several physicochemical parameters such as Temperature, Electric Conductivity, Dissolved Oxygen, Total Dissolved Solids, Salinity, Redox potential were measured in situ.

The development of Kaolinite geopolymer followed several stages ranging from preliminary treatment (grinding, sieving of raw kaolin), decarbonation with hydrochloric acid, extraction of clay fraction, formation of metakaolin and actual formation of geopolymer (Figure 1) using the cetyltrimethyl ammonium bromide (CTAB) activation method with in an alkaline medium following the procedures reported by Dazogbo [2].



Figure 1. Clay transformation: Raw clay (A) and elaborated geopolymer (B)

2.2. Analytical Methods

Relevant chemicals were hydrochloric acid (37 %), sodium hydroxide (97%), copper sulphate pentahydrate (98%), copper reagent (CuVer 1), Paracetamol (500 mg tablet), distilled water and geopolymer powder made from Kaolinite.

To carry out the tests and analyses, we used a range of laboratory equipment, the most relevant of which are: a mini-flocculator, a pH meter/thermometer, a UV-Visible spectrophotometer (DR500), Centrifuge (80-2), colorimeter (DR890) and a multiparameter probe (AQUARED).

The working (standard) solutions, which were used, are namely: Cu^{2+} (aq). 5 ppm, prepared by dissolving 39.3 mg of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ in 2 L of distilled water. Preliminary verification of the copper content was carried out by 4 tests and instead showed an average concentration of 4 ppm. The aqueous solution of 100 ppm of paracetamol

was obtained by dissolving 200 mg of paracetamol powder in 2 L of distilled water.

Indeed, Copper dosage was carried out at the Applied Hydrology Laboratory (LHA) using the colorimetric method with the DR890 colorimeter (program 20) based on the Beer-Lambert principle as shown by eq. (1), which relates the absorbance of a solution when it is crossed by light of a specific wavelength in a well-defined path, with the concentration of the absorbing species [12]. In the same purpose, the bicinchoninate technique was used (HACH method), where the cupric ions form a complex with the violet-colored bicinchoninic acid, which absorbs at 454 nm.

$$A = \varepsilon * l * c \quad \text{Eq. (1)}$$

Where A is the absorbance, ε denote the absorptivity constant ($\text{L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$), l is the optical distance (cm) and C is the concentration in $\text{mol} \cdot \text{L}^{-1}$.

Furthermore, Paracetamol concentration was

determined by UV-visible spectrophotometry, and the equation obtained during the calibration curve is presented in Figure 2. The DR500 UV-Visible spectrophotometer set to program 880 was used to read the absorbance.

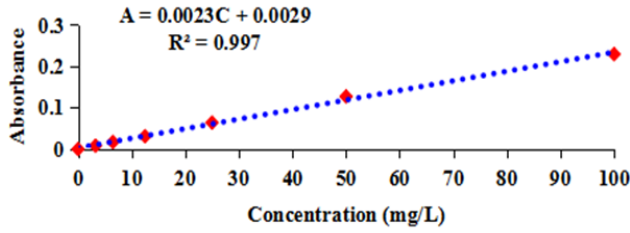


Figure 2. Calibration curve for paracetamol solution at $\lambda = 280$ nm

$$\Delta G_r^\circ(T) = \Delta E_{ads} + ZPE(X) - [E_{trans}(X) + E_{rot}(X)] - T [S_{trans}(X) + S_{rot}(X)] \quad \text{Eq. (3)}$$

With ΔE_{ads} the adsorption energy, ZPE is zero-point energy, E_{trans} is the translation energy, E_{rot} is the rotational energy, S_{trans} denote the translational entropy and S_{rot} is the rotational entropy.

3. Experimental Process

During the adsorption tests, the flocculation technique was used, and the yield was calculated using eq. (4).

$$R(\%) = 100 * \frac{C_0 - C_e}{C_0} \quad \text{Eq. (4)}$$

Where, C_0 denotes the initial concentration, C_e is the concentration at equilibrium.

To reduce the organic charges, 100 mL of liquid sample was taken to which the optimal mass of the geopolymer was added, and the mixture was stirred for a given time. At the end of adsorption, centrifugation was carried out and finally the analysis. The mass effect was obtained by the curve, $R(\%) = f(\text{mass})$, while that of the pH was determined at the pH with maximum absorbance. The kinetics of elimination was evaluated by the curve, $R(\%) = f(\text{contact time})$ and the maximum absorption capacity were obtained by the remainder method at different concentrations of the wastewater sample, with eq. (5).

By using the quantum chemistry modeling methods via VASP (Vienna Ab initio Simulation Package), the related eq. (2) was solved by specific pseudo-potentials of adsorption energy [13,14,15].

$$\Delta E_{ads} = E_{\text{Kaolinite-X}} - E_{\text{Kaolinite}} - E_X \quad \text{Eq. (2)}$$

Where E_{ads} is the adsorption Energy and X denote $\text{Cu}^{2+}/\text{Para}$.

The temperature effect on the molecule adsorption was determined by calculating the free energies of adsorption reactions ΔG_r° at different temperatures in eq. (3) [16]:

$$Q_a = V * \frac{C_0 - C_e}{m} \quad \text{Eq. (5)}$$

The isotherms were modeled by the Langmuir eq. (6) [17] and Freundlich eq. (7) [18]:

$$Q_e = \frac{Q_{\max} * K_L * C_e}{1 + K_L * C_e} \quad \text{Eq. (6)}$$

$$\log Q_e = \log K_F + \frac{1}{n} \log C_e \quad \text{Eq. (7)}$$

As for kinetic modelling, two most common models were used: Lagergren (Pseudo-First Order “PFO”) by eq. (8) and Blanchard (Pseudo-Second-Order “PSO”) using the eq. (9) [19,20]:

$$\ln(Q_e - Q_t) = \ln Q_e - K_1 t \quad \text{Eq. (8)}$$

$$\frac{t}{Q_t} = \left(\frac{1}{K_2} * \frac{1}{Q_e^2} \right) + \frac{t}{Q_e} \quad \text{Eq. (9)}$$

These kinetic models follow the thermodynamic equilibrium by the relation:

$$\Delta G^\circ = -RT \ln K^\circ \quad \text{Eq. (10)}$$

Which allowed deducing other kinetic parameters such as ΔG , ΔH and ΔS .

The levels of each parameter retained for optimization are shown in the following table. After defining the initial conditions for each test, batch tests were carried out to optimize the parameters, with each previously optimized parameter being used directly in the next test as described in Table 1.

Table 1. Levels retained for each parameter

Parameters	Levels										
Mass (g) (24 h)	0.01	0.02	0.03	0.05	0.07	0.1					
Contact time (min)	5	10	15	20	30	45	60	90	120	150	180
Stirring speed (rpm)	100	150	175	200	250	300					
pH	2	4	6	8	10						
Temperature (°C)	20	25	30	45	60						
Initial Concentration (ppm)	Cu	1	2	3	4						
	Para	10	20	30	40	50	60	80	100		

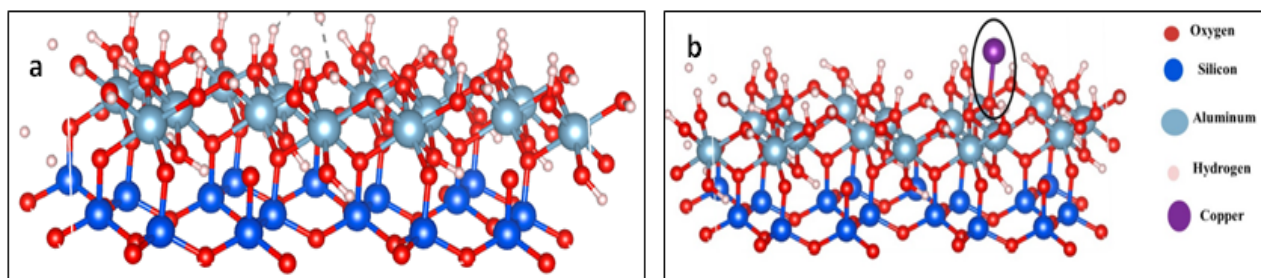


Figure 3. a) Free surface of kaolinite, b) Adsorption mechanism of Copper on Kaolinite Surface

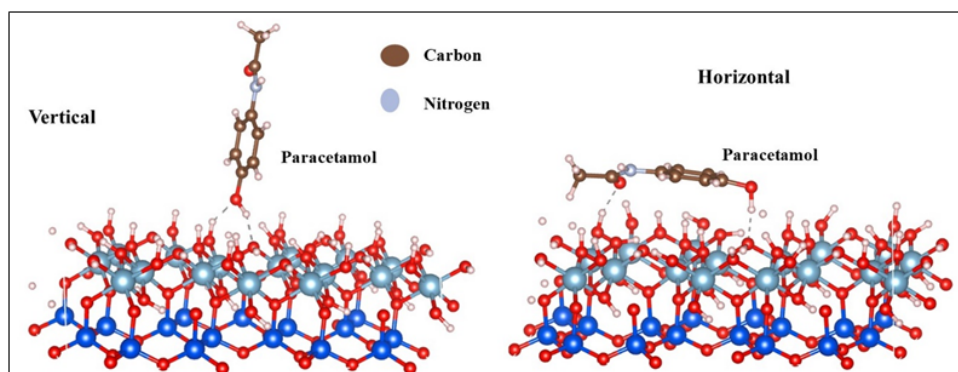


Figure 4. Adsorption mechanism of Paracetamol (vertical, Horizontal) on Kaolinite Surface

4. Results and Discussion

4.1. Adsorption by Quantum Chemistry Approach

The quantum chemistry predicted the deposition surfaces of copper in Figure 3 and paracetamol in Figure 4. It should be noted that the deposition of copper is unique and does not depend on orientation, only the forces of electrostatic attraction forces governing the deposition site of either on hydrogen ($-139.00 \text{ kJ.mol}^{-1}$) or on oxygen ($-139.15 \text{ kJ.mol}^{-1}$), while paracetamol could be deposited in two orientations, horizontal more favoured ($-159.40 \text{ kJ.mol}^{-1}$) than vertical ($-91.10 \text{ kJ.mol}^{-1}$) seen in Table 2.

The Figure 5 shows the profile of the variation of the free energy of adsorption as a function of temperature. These results therefore show that it is possible to regenerate kaolinite by heating it up to 435 K to eliminate the DR and to 780 K if it is TME. The removal of the adsorbed water during the process does not interfere in any way, since the kaolinite will always be in contact with the wastewater.

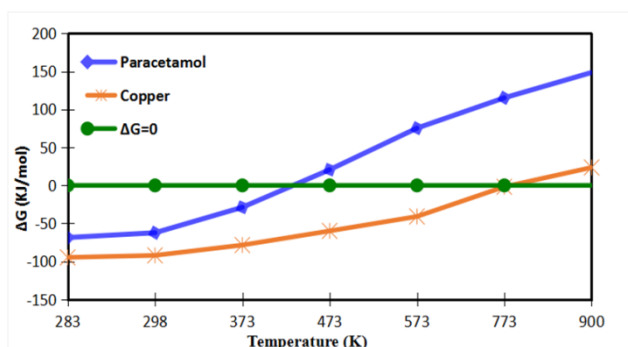


Figure 5. Evolution of adsorption energy of Copper and Paracetamol on Kaolinite surface

4.2. Adsorption by Experimental Approach

Table 3 reports the optimization procedure. It appears that all the parameters have an effect on the adsorption of TME and DR on kaolinite-geopolymer. The adsorption efficiency increases with the increase of the mass of the geopolymer as reported by several authors [21,22] and this is due to the availability of a greater number of sites on the Kaolinite surface.

Previous authors reported rapid adsorption of cupric ions on clays: Choumane [22] reached the equilibrium state at 20 minutes, while the result obtained by Chouchane et al. [23] perfectly matches that of this study, 30 minutes were enable for the equilibrium to be reached between the Cu^{2+} ions and the raw Kaolin powder in an aqueous medium. Gusain et al. [24] observed the same results during the removal of copper by modified sand. Bakhtiari & Azizian [25] also obtain an equilibrium time of 30 minutes by eliminating copper using nanoporous Metal-Organic Framework-5 (MOF-5). In the case of paracetamol, equilibrium was reached faster on Kaolinite at 25 minutes than on the material based on bentonite, cement and coal, which took 180 minutes [26]. However, this contact time is better within the range of 20-30 minutes as it was observed by Djemai and Boukrouk [27] on the elimination of Paracetamol by ZnFe_2O_4 for a yield of 57.97%. The Kaolinite geopolymer is more effective since its yield is 63% at this time.

In this study, we note that the optimum stirring speed for copper adsorption was 200 rpm such as in Chouchane et al. [23] but different from that reported by Melle [28] for whom the optimum value was of 400 rpm.

Moreover, for pH, the results show that the alkaline medium is the best; this is explained by the surface charge on the adsorbent material. The optimal temperature for the adsorption of copper is 30°C (303 K), while that of paracetamol is 25°C (298 K), on Geopolymer by kaolinite

and beyond these temperatures, the yield gradually decreases. These results were also reported by Khireddine *et al.* [29] during the adsorption of paranitrophenol on kaolinite intercalated with urea. Several authors have encountered this phenomenon; this is the case of Errais [30] during the adsorption of dye (Congo red) on kaolinite,

as well as the adsorption of trace metals on Thai kaolin and ball clay [31]. Therefore, the optimal concentrations are 1 ppm for copper but the yields are not far from other concentrations. For paracetamol it was 80 mg/L. The Table 3 gives the optimal level for the studied parameters.

Table 2. Adsorption energies and positions of Copper and Paracetamol on Kaolinite surface

Adsorbed Positions	Adsorption energies (kJ.mol ⁻¹)
Cu-H@Kaolinite	-139.00
Cu-O@Kaolinite)	-139.15
Para-Vertical@Kaolinite	-159.40
Para-Horizontal@Kaolinite	-91.10

Table 3. Optimal levels of the studied parameters

Adsorbate	Parameters					
	Mass (g)	Contact Time (min)	Stirring speed (rpm)	pH	T (°C)	Concentration (ppm)
Copper	0.07	30	200	8-9	30	1
Paracetamol	0.05	20	> 300	9-10	25	80

Table 4. Gibbs Energy, Enthalpy and Entropy (kJ.mol⁻¹) during adsorption of Copper and Paracetamol on Kaolinite surface

Copper					
T (K)	293	298	303	318	333
ΔH°	-12.700				
ΔS°	-0.014				
ΔG°	-8.470	-8.400	-8.330	-8.112	-7.891
Paracetamol					
ΔH°	-18.614				
ΔS°	-0.044				
ΔG°	-5.813	-5.601	-5.373	-4.723	-4.076

Table 5. Kinetic parameters of Pseudo-first order and Pseudo-second order adsorption models of Copper (4 ppm) and Paracetamol (80 ppm)

Model	Pseudo-First order					Pseudo-second order		
	K_1 (min ⁻¹)	R_1^2	Q_e cal (mg/g)	Q_e exp (mg/g)	K_2 (g/mg.min)	R_2^2	Q_e cal (mg/L)	Q_e exp (mg/g)
Copper	0.088	0.974	0.347	5.165	0.547	1	5.207	5.165
Paracetamol	0.094	0.666	16.622	114.701	0.011	0.997	116.302	114.70

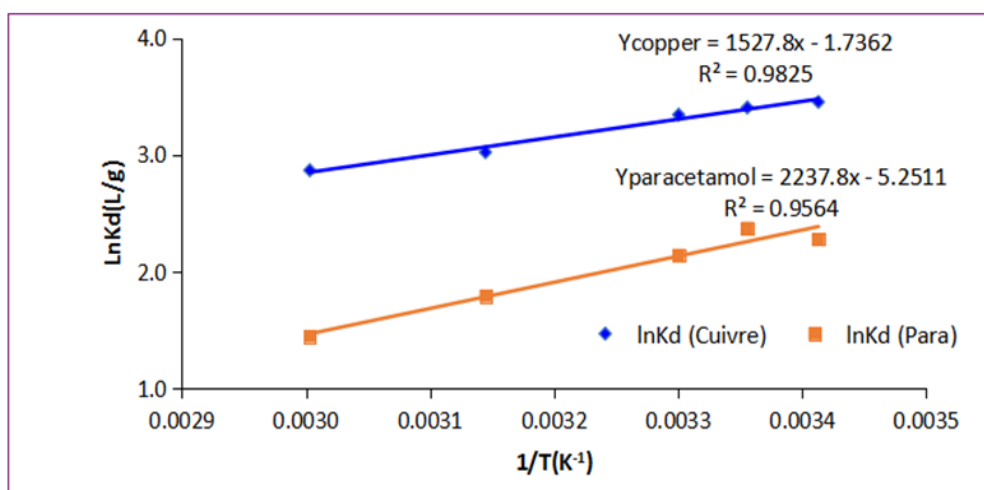


Figure 6. Profile of the distribution constant (Kd) and the Temperature

Starting from the relationship $\ln K_d = f(1/T)$ obtained on Figure 6, the calculated energy values (Table 4) show that all the enthalpies and Gibbs energies are negative, which implies that the adsorption of copper and paracetamol is exothermic and spontaneous.

The free energies obtained at optimal temperatures (303 K and 298 K) are respectively -8.33 kJ.mol⁻¹ and -5.60 kJ.mol⁻¹ and deviate widely from those calculated theoretically, this could be explained by modification of the structure of kaolinite during the formation of the

geopolymer, in the sense that it is heated to a high temperature and yet the DFT calculations are carried out on pure Kaolinite. However, these energies are higher than that obtained at 293 K ($-1.72 \text{ kJ.mol}^{-1}$) by Chouchane et al. [23] in the adsorption of copper, but very close to $-5.445 \text{ kJ.mol}^{-1}$, encountered at 298 K by Meriem & Mouad [26] in the adsorption of paracetamol on the composite material of clay-cement-coal.

These values which are between 0 and 40 kJ.mol^{-1} , correspond to the physisorption type adsorption energy which is exothermic and would be linked to electrostatic interactions [24,29,30], in the sense that the paracetamol which forms weak interactions also showed a low energy as predicted theoretically for a vertical attack ($-91.1 \text{ kJ.mol}^{-1}$) where there are fewer hydrogen bonds formed than for the horizontal attack ($-159.4 \text{ kJ.mol}^{-1}$) giving the possibility of forming more bonds.

The fact that the Entropy values are negative and very low shows that the adsorption of paracetamol and Cu does not lead to significant molecular and structural disorder either in the adsorbate level or at the adsorbent level [32]. This makes the elaborated Geopolymer an ideal material for this elimination, which can be used several times and maintain its effectiveness.

4.3. Adsorption Capacity

4.3.1. Kinetic Modeling

The simulation of adsorption kinetics was carried out according to Lagergren's law for pseudo-first order, while that of pseudo-second order by Blanchard's law. The calculated values obtained for the rate constant, the coefficient of determination and the maximum adsorption capacity are summarized in Table 5. For both adsorbates, it turns out that the Blanchard model better represents the adsorption mechanism on kaolinite. The coefficients of determination for the regressions are closed to 1 ($R^2 > 0.99$). The calculated values by the kinetic modelling equations show a maximum adsorption capacity per gram of kaolinite of 5.207 mg of copper for a solution concentration of 4 mg/L , and 116.302 mg in that of paracetamol for a concentration of 80 mg/L , which are very close to the Q_e values obtained experimentally, i.e., 5.165 and 114.70 mg/g respectively, which confirms that pseudo-second order kinetics better describes this phenomenon.

The simulation of the kinetic adsorption models shows that the pseudo-second order model is totally similar with the experimental model (Figure 7), which shows that the latter better simulates this adsorption, and this corroborates with the observation according to their R^2 value according to which that of copper was greater than that of Paracetamol.

4.3.2. Isotherm Modeling

The isotherms were drawn for the parameterized tests in the same way as the kinetic study. By plotting the adsorption capacity as a function of residual concentration at equilibrium ($Q_e = f(C_e)$), the plot gave the isotherms presented in Figure 8. Based on their appearance, that of copper is of the "C" type isotherm, while that of Paracetamol is of the "S" type according to the classification of Giles et al. [33]. However, according to Brunauer [34], the adsorption isotherm of copper is of type III and that of Paracetamol in type V.

The modelling of the isotherm was carried out according to the Langmuir and Freundlich models described by the equations, at different concentrations. The results obtained are presented in Table 6. Based on these isotherms, the adsorption of copper on the Kaolinite-based geopolymer is well represented by the two models; their determination indices are greater than 0.99, that of Langmuir ($R^2 = 0.997$) slightly outweighs that of Freundlich ($R^2 = 0.993$).

The same observation is valid during the adsorption of paracetamol, although the coefficients are low ($R^2 < 0.95$) and that of Langmuir is larger than that of Freundlich. The adsorption capacities calculated by the Langmuir equation are: 25.97 mg/g for copper and 181.82 mg/g for paracetamol. The adsorption speed of copper is faster than that of paracetamol as illustrated by their Langmuir constants.

The simulation of the isotherms according to the Langmuir and Freundlich equations produced isotherm profiles are presented in Figure 9. The simulated Langmuir model is completely similar with that of Freundlich; this is explained by their coefficients of determination, which are very close for the linearized equations. However, for the two substances, the experimental isotherm is well matched to the others in low concentrations only and the non-alignment is very pronounced in the adsorption of paracetamol.

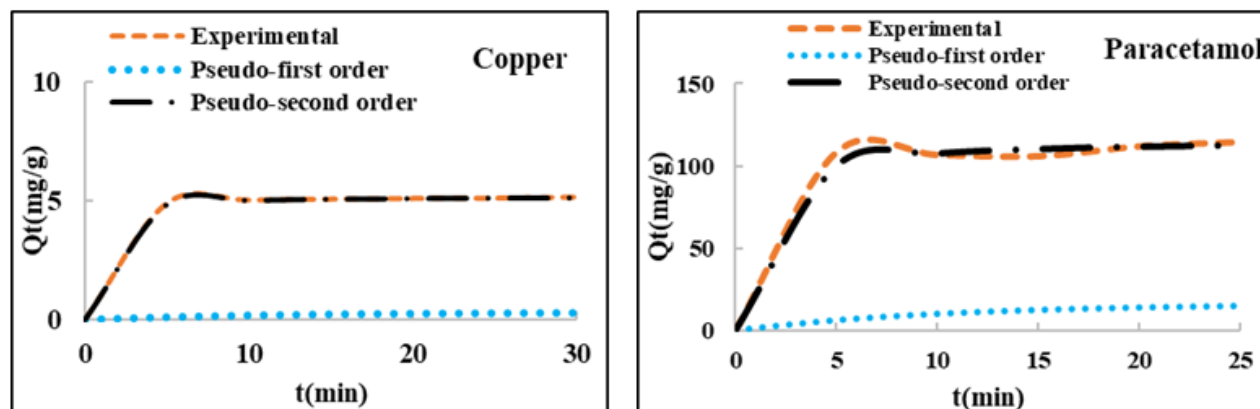


Figure 7. Simulation of kinetic models of adsorption of Copper and Paracetamol on Kaolinite Surface

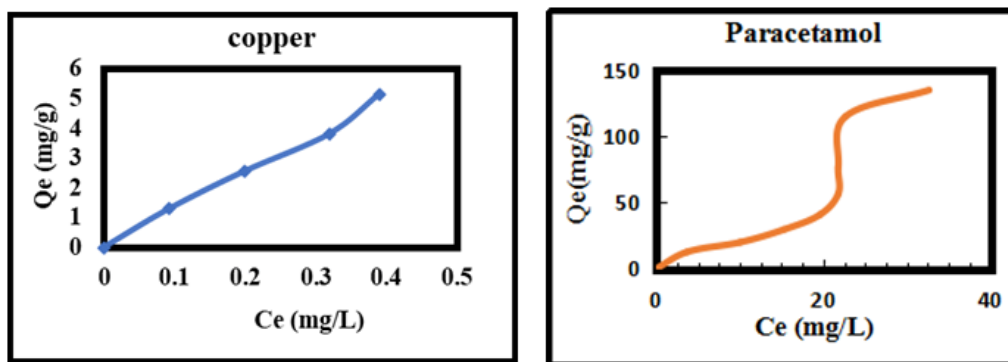


Figure 8. Adsorption isotherms of Copper and Paracetamol on Kaolinite Surface

Table 6. Parameters of the Langmuir and Freundlich models of Copper and Paracetamol adsorbed on Kaolinite Surface

Adsorbate	Parameters							
	Langmuir Model			Freundlich Model				
	$Q_{max} (exp)$ (mg/g)	$Q_{max} (cal)$ (mg/g)	R^2	K_L (L/mg)	K_F (L/g)	n	$1/n$	R^2
Copper	5.165	25.97	0.997	0.568	11.64	1.10	0.93	0.993
Paracetamol	114.70	181.82	0.871	0.019	2.14	0.90	1.11	0.818

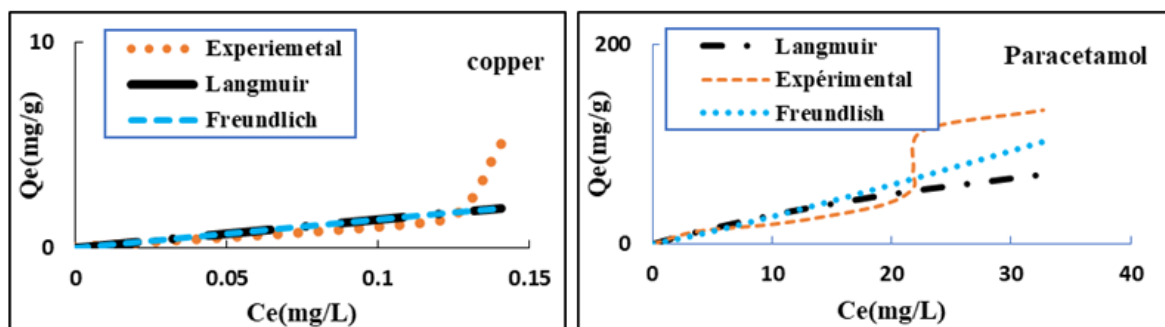


Figure 9. Adsorption isotherms simulation of Copper and Paracetamol on Kaolinite Surface

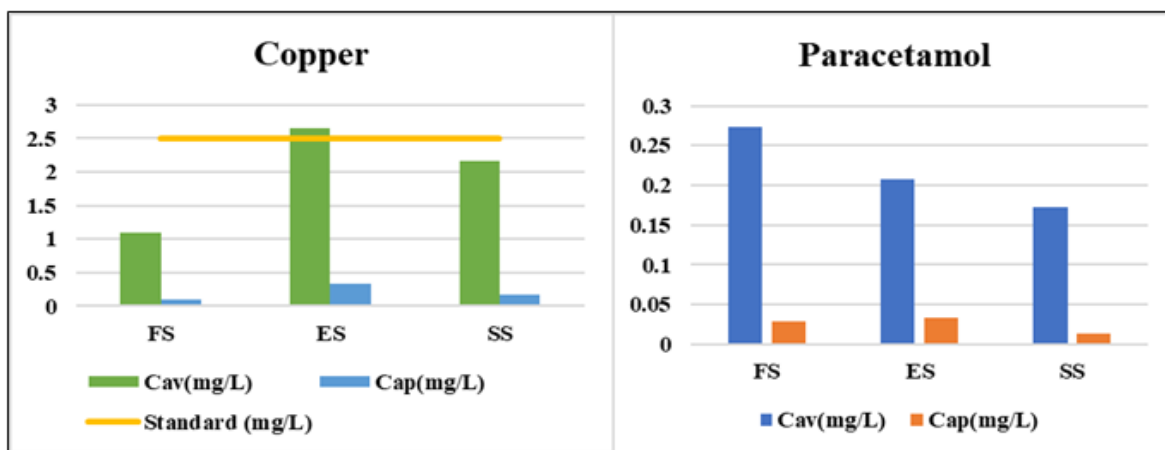


Figure 10. Variation in the concentration of Copper and Paracetamol compared to the discharge standard before and after treatment with Kaolinite (Cav: Concentration before treatment, Cap: Concentration after treatment, FS: Septic tank, ES: WWT entry, SS: WWT exit)

4.4. Application to Wastewater Treatment

The copper and paracetamol concentrations in the wastewater were determined before (Cav) and after (Cap) treatments. The obtained values made possible the calculation of the adsorption efficiencies. From the results, we noted that only the ES site before treatment has a copper concentration higher than the Beninese standard

for discharge into the receiving environment. This concentration is 2.93 mg/L lower than that encountered by Todedji et al. [35] in wastewater at the entrance to the CHU-MEL WWTP. The treatment of hospital wastewater gave an average yield of $90.5 \pm 2.10\%$, which shows that this Kaolinite process is very effective for the elimination of copper in wastewater. The concentrations found after treatment vary from 0.013 to 0.034 mg/L. In the

elimination of paracetamol, the process gave an average yield of $88.5 \pm 3.65\%$.

Table 7. Reduction rates of the concentration of copper and paracetamol after treatment with kaolinite (FS: Septic tank, ES: WWT entry, SS: WWT exit)

	Reduction rate (%)	
	Copper	Paracetamol
FS	91,8	89,4
ES	87,5	83,7
SS	92,2	92,5
Average	$90,5 \pm 2,10$	$88,5 \pm 3,65$

5. Conclusion

The aim of this study to assess and optimize the adsorption method of copper ions and paracetamol on kaolinite adsorbent industrial wastewater treatment purpose. The study started with a quantum chemical investigation for the prediction of the adsorption mechanism. The second step consisted of batch test experiments in aqueous solutions of copper and paracetamol and the last one was the application of the optimized method to industrial wastewater collected. The results brought us to the following conclusions: the alkaline activation Kaolinite under the CTAB showed a reduction rate in the copper concentration of 90.3% and 71.7% in the aqueous standard solutions for Cu^{2+} (4 mg. L^{-1}) and paracetamol (80 mg/L). For hospital wastewater, the study revealed elimination rates of $90.5 \pm 2.10\%$ and $88.5 \pm 3.65\%$ from the respective contents of copper and paracetamol.

This investigation contributed to the improvement of a procedure for using the adsorbent potential of Ketou kaolinite clay, and may be profitable in the treatment of industrial wastewater to combat aquatic-ecosystem health degradation due to pollution by emerging micro-pollutants. It is noted that only the behaviours of Copper and Paracetamol on the geopolymer have been studied and their representativeness in the respective chemical classes remains insignificant. Therefore, the extension of this study to other micro-pollutants is a necessary and useful prospect.

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