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Review Article

Characterisation, Performance, and Kinetics of Kaolin-Based Adsorbents for Advanced Wastewater Treatment

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Abstract *- Kaolin, a naturally abundant aluminosilicate clay, has emerged as a promising candidate for sustainable and low-cost environmental remediation. This study investigates the physicochemical characteristics and adsorption efficiency of untreated Kaolin in removing multiple pollutants, such as turbidity, chemical oxygen demand (COD), and lead (Pb^{2+}) from simulated wastewater. Characterization analyses revealed a BET specific surface area of 13.967 m^2/g, confirming its adsorption potential. Thermogravimetric analysis indicated excellent thermal stability up to 950 °C, while Fourier transform infrared (FTIR) spectroscopy identified surface functional groups such as hydroxyl and silanol, responsible for adsorptive interactions. Batch adsorption experiments were conducted using the simulated wastewater containing 300 NTU turbidity, 800 mg/L COD, and 10 mg/L Pb^{2+} at a neutral pH of 6.5. Kaolin doses ranging from 0.5 to 5 g/L were tested. Optimal removal efficiencies were observed at 5 g/L, achieving 91.8% reduction in turbidity, 77.7% in COD, and 86.5% in Pb^{2+}. Adsorption kinetics followed a pseudo-second-order model, indicating that chemisorption governs the removal mechanism, which conforms to ion exchange and surface complexation. Unlike many researchers whose studies are based upon modified or chemically treated clays, this work demonstrates that raw, unmodified Kaolin exhibits excellent multifunctional performance in treating complex wastewater systems. The findings underscore Kaolin's potential as a scalable, environmentally benign adsorbent for decentralized and industrial water treatment applications. This research fills a critical gap in the literature and supports the broader adoption of natural clays as green alternatives for integrated pollutant removal.*

Keywords *- Wastewater treatment, COD removal, Lead adsorption, Turbidity reduction, Adsorption kinetics.*

1. Introduction

Rapid industrialisation, urbanisation, and the expansion of agricultural activities have significantly increased environmental pollution worldwide [1], [2]. Among the most critical issues are the contamination of water bodies with heavy metals, synthetic dyes, organic pollutants, and industrial effluents [3], [4]. These pollutants pose serious ecosystem risks and threaten human health through bioaccumulation and biomagnification in the food chain [5]. Pollutants like lead, cadmium, chromium, arsenic, mercury, and various dyes are commonly found in industrial discharges from mining, textile, leather, electroplating, and chemical manufacturing industries [6]. Due to their non-biodegradable nature, many contaminants persist in the environment, making their removal an urgent priority [7].

Traditional wastewater treatment methods, such as chemical precipitation, ion exchange, reverse osmosis [8], and membrane filtration, often suffer from high operational costs, secondary pollution, and limited effectiveness, particularly at low contaminant concentrations [9]. Therefore, there is an increasing demand for cost-effective, eco-friendly, and efficient materials that can be employed in adsorption-based remediation techniques [10]. Adsorption is widely recognised for its simplicity, efficiency, low cost, and potential for regeneration, making it a favourable method for pollutant removal [11]. Adsorption stands out as one of the most promising treatment methods due to its operational simplicity, regeneration potential, and economic viability. Natural adsorbents, particularly clay minerals, have attracted considerable interest for their utility in various applications. Among these clay minerals, kaolin is exceptional due to its availability. It exhibits several advantageous properties, including chemical inertness, thermal stability, and surface reactivity arising from its modifiable hydroxyl groups.

Kaolin is predominantly composed of kaolinite ($Al_2Si_2O_5(OH)_4$), a 1:1 layered phyllosilicate consisting of alternating tetrahedral silica and octahedral alumina sheets. This layered configuration imparts both structural stability and notable adsorption capacity [12]. The interlayer hydrogen bonding renders kaolinite non-expandable and more stable compared to other clays such as montmorillonite. In addition to its fine particle size and high specific surface area, kaolin's chemical inertness enhances its suitability for a wide range of industrial uses, including in ceramics, paper manufacturing, paints, pharmaceuticals, and environmental remediation as a sorbent [13]. Furthermore, the presence of surface hydroxyl groups facilitates functionalization, thereby expanding its potential for targeted or enhanced performance in specific applications.

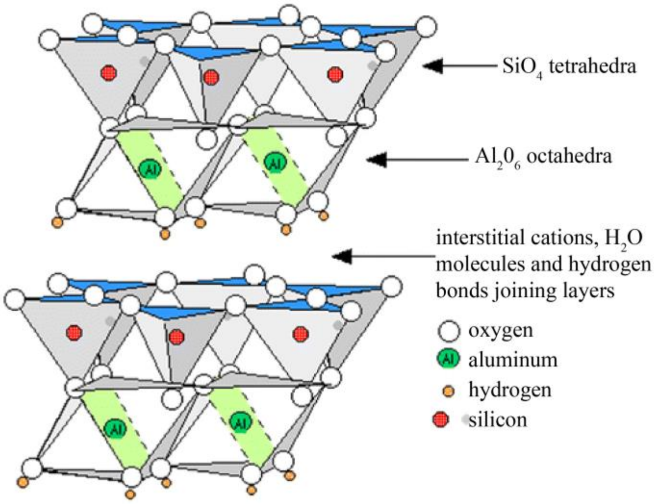


Fig. 1 Structure Showing Two Layers of the Stacked Sheets of Kaolinite [13]

The surface area and porosity of kaolin are key factors that determine its effectiveness in a range of industrial and environmental uses, including its roles in adsorption, catalysis, and ceramic production [14]. In its natural state, kaolin typically exhibits a specific surface area between 10 and 20 m²/g, though this can vary based on its crystallinity, particle size, and the processing techniques employed. When subjected to acid or thermal activation, kaolin often undergoes a notable increase in surface area value of between 50 and 100 m²/g. This increased surface area enhances its chemical reactivity and adsorption capabilities [15].

In its raw form, kaolin is generally classified as a material with low porosity, possessing a limited internal pore volume [16]. Its pore structure mainly comprises inter-particle voids rather than natural internal pores. The pore diameter in natural Kaolin tends to be in the mesoporous range between 2–50 nm when modified, but is often minimal in untreated samples [15]. Particle size, morphology, crystallinity, and modification methods affect surface area and porosity. These properties make Kaolin useful as an adsorbent, catalyst support, and in barrier coatings when tailored appropriately [17].

Kaolin has a low and variable surface charge compared to other clay minerals like smectite or montmorillonite [18]. Its surface charge arises mainly from the isomorphic substitution and the dissociation of surface hydroxyl groups located on the edges of the crystals. Permanent charge is minimal due to limited isomorphic substitution within the crystal lattice [19]. For the pH-dependent charge, the dominant form of surface charge is Kaolin. The charge develops primarily at the edges of the Kaolinite platelets as hydroxyl groups (–OH) gain or lose protons, depending on the pH [14]. At low pH, the surface tends to be positively charged (protonated edges). At high pH, the surface tends to be negatively charged (deprotonated edges) [20]. Thus, Kaolin's surface charge is variable and pH-sensitive, unlike the permanent negative charge in smectite clays [21]. It has a low cation exchange capacity, typically in the range of 3 to 15 meq/100g, depending on its purity, particle size, and degree of crystallinity [22]. The reasons for low cation exchange capacity (CEC) are limited isomorphic substitution in the Kaolinite structure, lack of interlayer spaces for ion exchange and smooth basal surfaces with few exchange sites [23]. The implications of surface charge and CEC are adsorption properties, stability, and surface modification potential [24].

Ismail et al. (2019) reported that while untreated kaolin can remove COD, BOD, turbidity, and suspended solids, most of their study emphasized thermally treated kaolin, noting that the treated form showed higher adsorption efficiency and completely leaving the role of untreated kaolin [25]. Daud et al. (2020) focused specifically on kaolin's capacity to remove COD and ammonia nitrogen from natural rubber wastewater but did not investigate heavy metals or turbidity, thereby limiting the understanding of kaolin's multi-functional capabilities in more complex contaminant matrices [26]. Hussain & Ali (2021) studied the adsorption of lead (Pb^{2+}) using untreated kaolin but confined their experiments to single-metal systems, with no inclusion of organic or turbidity parameters. They acknowledged that kaolin is effective in removing lead, yet did not extend findings to mixed pollutant conditions [27]. Mustapha et al. (2019) evaluated untreated kaolin for tannery wastewater but emphasized the need for pretreatment to enhance performance. Their findings supported kaolin's cost-effectiveness, yet their work still leaned on improving raw kaolin, suggesting limited confidence in its standalone performance [15]. These authors reported limitations collectively reveal a pressing need for comprehensive studies evaluating untreated kaolin's effectiveness under real-world, multi-pollutant, and variable environmental conditions.

In contrast, the uniqueness of this present study lies in its direct evaluation of untreated and unmodified kaolin clay for the simultaneous removal of turbidity, chemical oxygen demand (COD), and lead (Pb^{2+}) from synthetic wastewater. Unlike previous works that isolate single pollutant types or prioritize modified kaolin forms, this research investigates raw kaolin's multi-functionality under integrated pollutant conditions that closely simulate real wastewater scenarios. This fills a substantial knowledge gap by providing new evidence on the practical applicability and environmental viability of using raw kaolin without chemical or thermal enhancement.

2. Materials and Methods

The Kaolin sample used for this study is sourced from a village in Isiala Ngwa in Abia State. It was crushed to fine powder and sieved using an electric sieve to a 100 µm particle size.

2.1. Characterisation of Kaolin

Kaolin's structural, thermal, and surface properties were analysed using FTIR, TGA, XRD and BET surface area measurements as described in [28].

2.2. Wastewater Simulation and Treatment

A synthetic wastewater solution was prepared, containing clay, glucose and Lead (Pb^{2+}). The homogenous wastewater solution was treated with varying doses of Kaolin (0.5-5 g/L). The efficiency of Kaolin was evaluated based on turbidity reduction (Nephelometric Turbidity Units - NTU), COD removal efficiency (%), heavy metal reduction (%), and pH Changes. These parameters were measured before and after treatment.

2.3. Adsorption Kinetics of Kaolin in Wastewater Treatment

The adsorption behaviour of kaolin toward various pollutants, including heavy metals and organic compounds, is usually analysed using kinetic models that characterize the rate and efficiency of contaminant removal. In this context, the Pseudo-First-Order (PFO), Pseudo-Second-Order (PSO), and Intraparticle Diffusion (IPD) models are typically employed to simulate and interpret the adsorption kinetics.

3. Results and Discussion

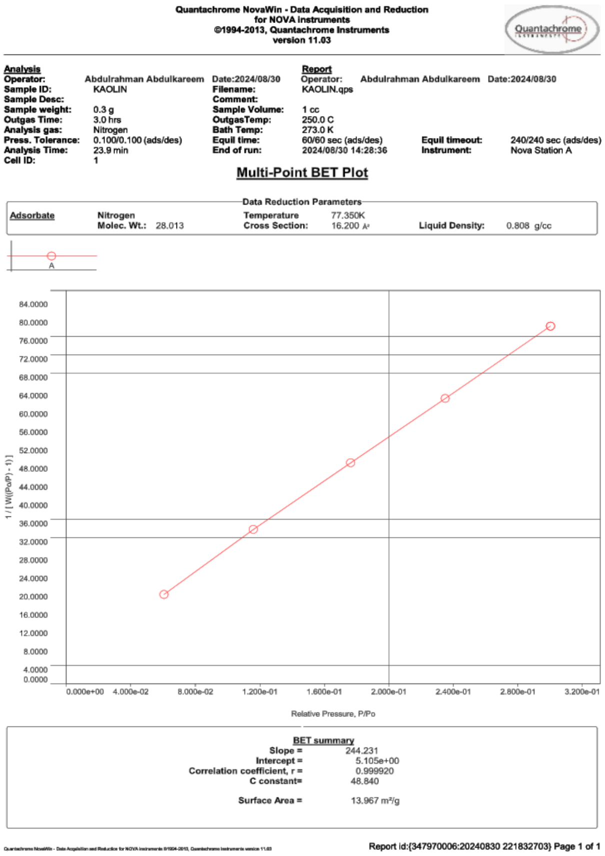
3.1. Characterisation Techniques for Kaolin as an Adsorbent

A comprehensive characterization of kaolin was performed using Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), Brunauer–Emmett–Teller (BET) surface area analysis, and X-ray diffraction (XRD). These analytical techniques collectively offer detailed information on the material's functional groups, thermal stability, crystallographic structure, and specific surface area.

3.1.1. Brunauer-Emmett-Teller (BET) Surface Area Analysis for Kaolin

The specific surface area of the kaolin sample was measured as 13.967 m²/g using the Brunauer–Emmett–Teller (BET) method. This surface area reflects the material's capacity for adsorption, which is critical for its performance in catalytic applications and adsorption systems, as well as a reinforcing agent in composite materials [29]. The linear BET plot depicted in Figure 2a validates the suitability of the BET model for this analysis. Additionally, the high correlation coefficient (r = 0.999920) confirms the robustness and accuracy of the surface area measurement. The slope and intercept of the BET plot are 244.231 and 5.105, respectively, with a C constant of 48.840. The C constant reflects the energy of adsorption, where a higher value suggests stronger interactions between the adsorbate (nitrogen) and the surface of the Kaolin sample.

The surface area result aligns with typical values for Kaolin, which generally range between 10 and 20 m²/g [18], [30]. This confirms that the sample exhibits characteristics consistent with naturally occurring Kaolinitic clays. The moderately high surface area is beneficial for its use in applications where adsorption or interaction with other materials is required, such as in adsorption processes or as a filler in polymer composites.



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Sample Desc:
Sample weight: 0.3 g
Outgas Time: 3.0 hrs
Analysis gas: Nitrogen
Press. Tolerance: 0.100/0.100 (ads/des)
Analysis Time: 23.9 min
Cell ID: 1

Report
Operator: Abdulrahman Abdulkareem Date:2024/08/30
Filename: KAOLIN.qps
Comment:
Sample Volume: 1 cc
OutgasTemp: 250.0 C
Bath Temp: 273.0 K
Equil time: 60/60 sec (ads/des)
End of run: 2024/08/30 14:28:36
Equil timeout: 240/240 sec (ads/des)
Instrument: Nova Station A

Multi-Point BET Plot

Data Reduction Parameters
Adsorbate: Nitrogen
Molec. Wt.: 28.013
Temperature 77.350K
Cross Section: 16.200 Å²
Liquid Density: 0.808 g/cc

BET summary
Slope = 244.231
Intercept = 5.105e+00
Correlation coefficient, r = 0.999920
C constant= 48.840

Surface Area = 13.967 m²/g

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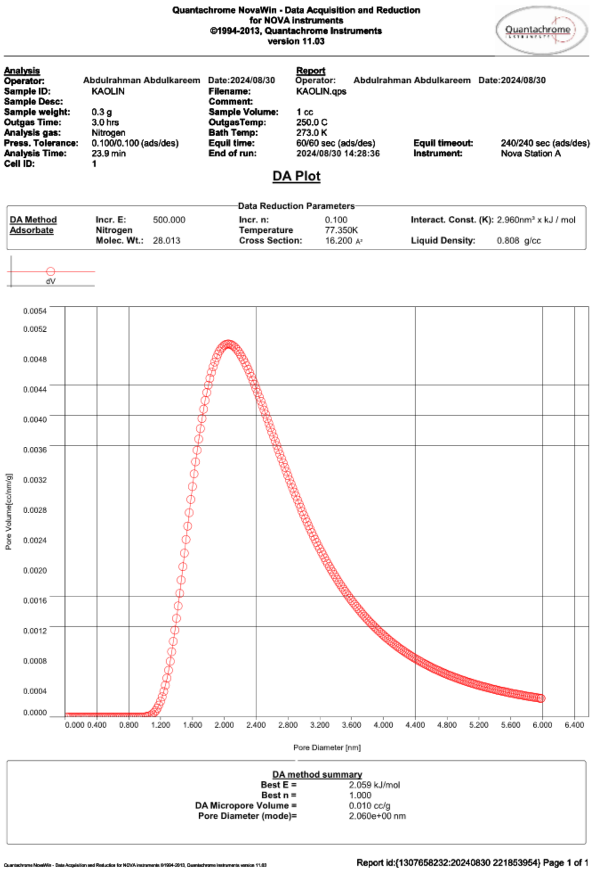
Fig. 2(a) BET Surface Area Analysis for Kaolin

Figure 2b shows the adsorption properties of a Kaolin sample, with the x-axis representing the relative pressure (P/Po) and the y-axis representing the adsorbed volume (STP) in cc/g. The red curve indicates how the Kaolin sample adsorbs gas at different pressures. The shape of the graph shows the type of adsorption isotherm.

The initial steep rise at low relative pressures suggests the presence of micropores. The plateau at higher pressures indicates the completion of monolayer coverage and the beginning of multilayer adsorption. This data can be used to calculate the specific surface area and pore volume of the Kaolin sample.



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Press. Tolerance: 0.100/0.100 (ads/des)
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End of run: 2024/08/30 14:28:36

Report
Operator: Abdulrahman Abdulkareem Date:2024/08/30
Equil timeout: 240/240 sec (ads/des)
Instrument: Nova Station A

DA Plot

Data Reduction Parameters
DA Method
Adsorbate
Incr. E: 500.000
Nitrogen
Molec. Wt.: 28.013
Incr. n: 0.100
Temperature 77.350K
Cross Section: 16.200 Å²
Interact. Const. (K): 2.960nm³ x kJ / mol
Liquid Density: 0.808 g/cc

DA method summary
Best E = 2.059 kJ/mol
Best n = 1.000
DA Micropore Volume = 0.010 cc/g
Pore Diameter (mode)= 2.060e+00 nm

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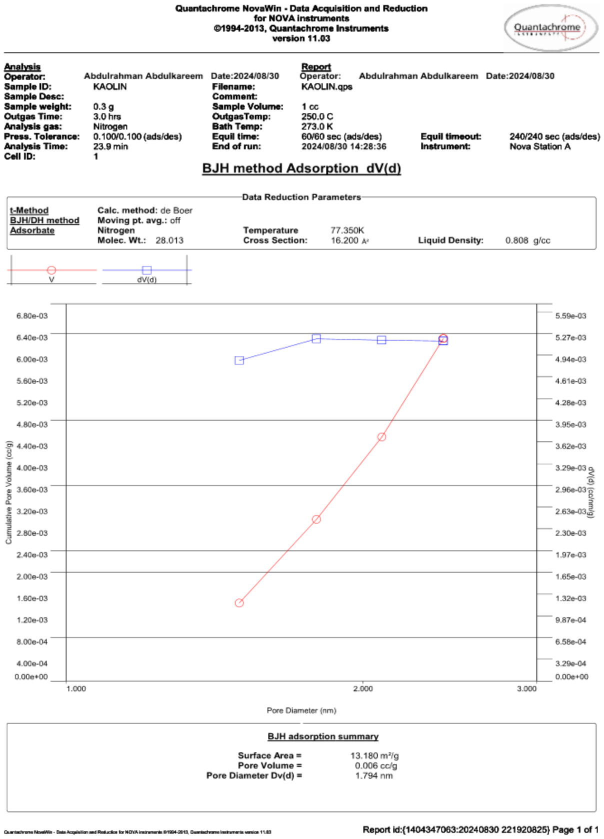
Fig. 2(b) BET Surface Area Analysis for Kaolin

The Kaolin sample was outgassed at 250 °C for 3 hours to remove moisture and contaminants. Nitrogen was used as the analysis gas. Figure 2c shows the pore volume against pore diameter. Significant peaks in the graph indicate the most common pore sizes. The kaolin sample exhibited a specific surface area of 13.180 m²/g and an average pore diameter of 1.794 nm, as determined through BET analysis. A higher surface area enhances the availability of active sites, which is advantageous for adsorption and catalytic processes, thereby improving the material's functional performance [31]. The total pore volume measured at 0.006 cc/g provides additional characteristic capacity for adsorbate or reactant accommodation. The moderate porosity and appreciable surface area indicate that the kaolin sample possesses favourable properties for deployment in diverse industrial applications.

3.1.2. Thermogravimetric Analysis (TGA) for Kaolin

Figure 3a illustrates the thermogravimetric behaviour of the kaolin sample subjected to heating from 30 °C to 950 °C at a constant rate of 10 °C/min. An initial weight loss observed between 30 °C and 200 °C is attributed to the release of physically adsorbed moisture from the kaolin surface. The most pronounced mass reduction occurs between approximately 450 °C and 600 °C, corresponding to the dehydroxylation of kaolinite ($Al_2Si_2O_5(OH)_4$), during which hydroxyl groups are eliminated, resulting in the formation of metakaolin ($Al_2Si_2O_7$) and structural reconfiguration of the material [32]. Beyond 600 °C, the weight loss levels off, indicating thermal stabilization of the sample, with negligible decomposition occurring up to 950 °C. The cumulative weight loss over the entire temperature range is about 70%, reflecting both desorption of water and dehydroxylation processes. These findings align with the characteristic thermal profile of kaolin and confirm its transformation into a more thermally stable phase, consistent with metakaolin formation.



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Analysis
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Outgas Time: 3.0 hrs
Analysis gas: Nitrogen
Press. Tolerance: 0.100/0.100 (ads/des)
Analysis Time: 23.9 min
Cell ID: 1

Filename: KAOLIN.qps
Comment:
Sample Volume: 1 cc
OutgasTemp: 250.0 C
Bath Temp: 273.0 K
Equil time: 60/60 sec (ads/des)
End of run: 2024/08/30 14:28:36

Report
Operator: Abdulrahman Abdulkareem Date:2024/08/30
Equil timeout: 240/240 sec (ads/des)
Instrument: Nova Station A

BJH method Adsorption dV(d)

Data Reduction Parameters
t-Method
BJH/DH method
Adsorbate
Calc. method: de Boer
Moving pt. avg.: off
Nitrogen
Molec. Wt.: 28.013
Temperature 77.350K
Cross Section: 16.200 Å²
Liquid Density: 0.808 g/cc

BJH adsorption summary
Surface Area = 13.180 m²/g
Pore Volume = 0.006 cc/g
Pore Diameter Dv(d) = 1.794 nm

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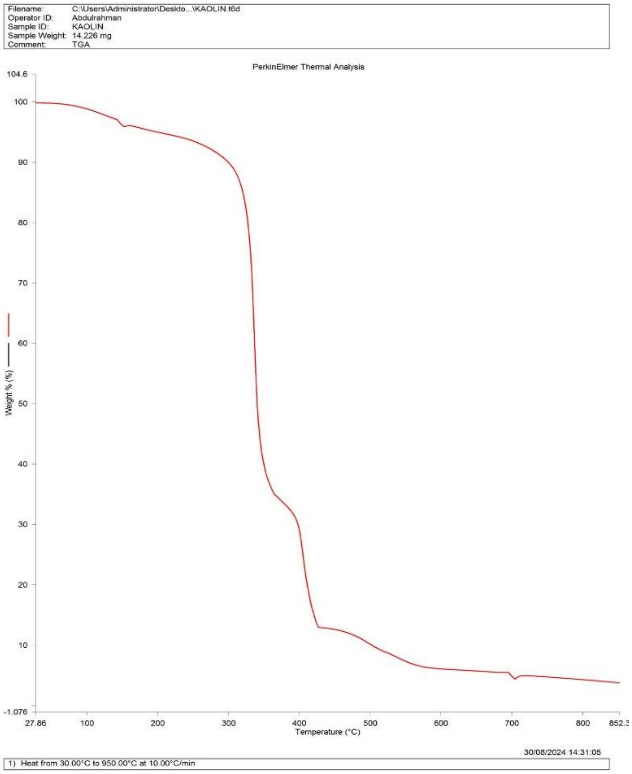
Report id:{1404347063:20240830 221920825} Page 1 of 1

Fig. 2(c) Analysis of Pore Size Distribution and Surface Area of Kaolin via the Barrett–Joyner–Halenda (BJH) Method

Figure 3b presents integrated Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) data, offering a comprehensive evaluation of the thermal behaviour and compositional evolution of the kaolin sample. The initial mass loss associated with the evaporation of adsorbed water and the obvious dehydroxylation at elevated temperatures depict kaolin's intrinsic thermal responses. These transformations are pivotal in determining kaolin's performance and stability in thermally demanding applications. A detailed understanding of these thermal characteristics enhances the ability to tailor kaolin for specific industrial uses, such as ceramics, cementitious systems, and high-temperature composites.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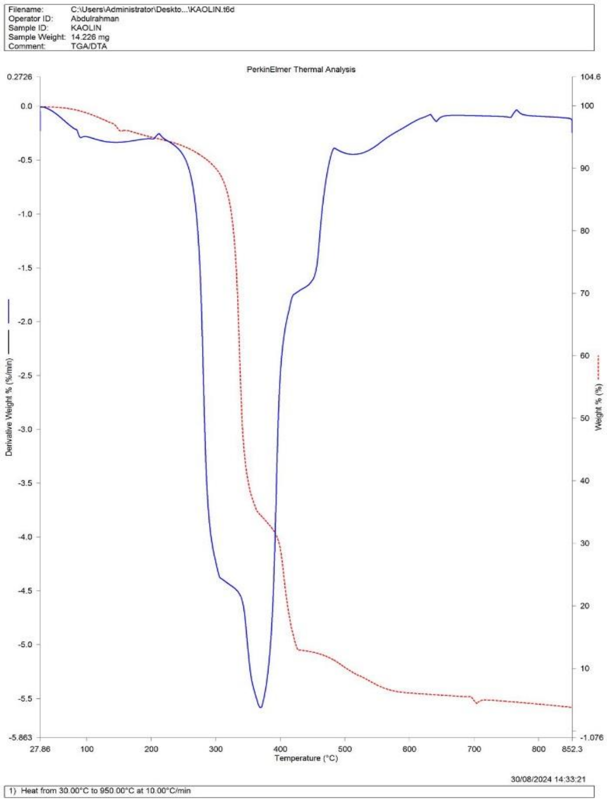
Sample ID: KAOLIN
Sample Weight: 14.226 mg
Comment: TGA

1) Heat from 30.00°C to 950.00°C at 10.00°C/min

Fig. 3(a)TGA for Kaolin


Filename: C:\Users\Administrator\Deskto...\KAOLIN.t6d
Operator ID: Abdulrahman
Sample ID: KAOLIN
Sample Weight: 14.226 mg
Comment: TGA/DTA

1) Heat from 30.00°C to 950.00°C at 10.00°C/min

Fig. 3(b) TGA for Kaolin

3.1.3. Fourier Transform Infrared Spectroscopy (FTIR) Analysis for Kaolin

Infrared (IR) spectroscopy serves as a robust analytical method for elucidating functional groups and investigating the molecular architecture of materials. As depicted in Figure 4, the prominent absorption bands at 3697.5 cm^{-1} and 3373.2 cm^{-1} are indicative of hydroxyl groups, which are intrinsic to the layered framework of kaolin and play a crucial role in determining its physicochemical behaviour [34]. The absorption band observed at 1636.3 cm^{-1} is attributable to molecular water adsorbed onto the kaolin surface, a common feature among clay minerals due to their capacity to retain water in both surface sites and interlayer voids [16]. Additionally, the bands at 998.9 cm^{-1}, 797.7 cm^{-1}, and 909.5 cm^{-1} corroborate the presence of silicate units, corresponding to characteristic Si–O stretching and bending vibrations. The absorption feature at 2124.6 cm^{-1} may be associated with trace impurities, potentially organic in nature, which could stem from either the raw material's natural heterogeneity or contamination introduced during sample preparation [20]. Collectively, the IR spectral data affirm the structural constituents of the kaolin sample, namely hydroxyl groups, bound water, and silicate frameworks. These are fundamental to its functionality across a range of industrial applications.

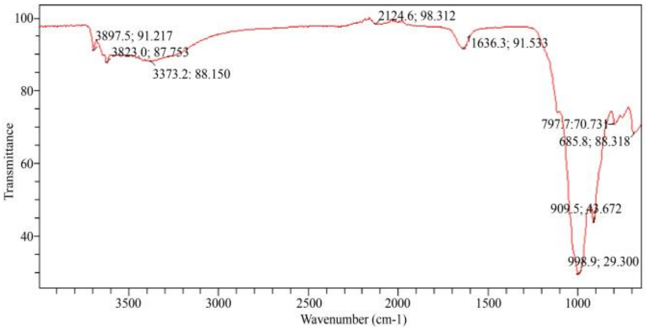


Fig. 4 FTIR Analysis for Kaolin

3.1.4. X-Ray Diffraction (XRD) Analysis for Kaolin

The mineralogical characterization presented in Figures 5a and 5b underscores the suitability of the kaolin sample for use as a bio-adsorbent, largely attributed to the identified presence of clay minerals, notably kaolinite and montmorillonite. These minerals are well-documented for their high surface area, layered structure, and ion-exchange capacities, which collectively enhance their adsorption performance in environmental and industrial applications.

Both qualitative and quantitative assessments provide a deeper understanding of their suitability for various adsorption applications, including environmental remediation and water purification. The qualitative XRD analysis confirms the presence of Kaolinite-1A, Montmorillonite, Quartz, Orthoclase, Illite, and Muscovite, while the quantitative analysis assigns specific weight fractions to these minerals, as shown in Table 1.

Table 1. Mineralogical Composition and Its Relevance to Adsorption

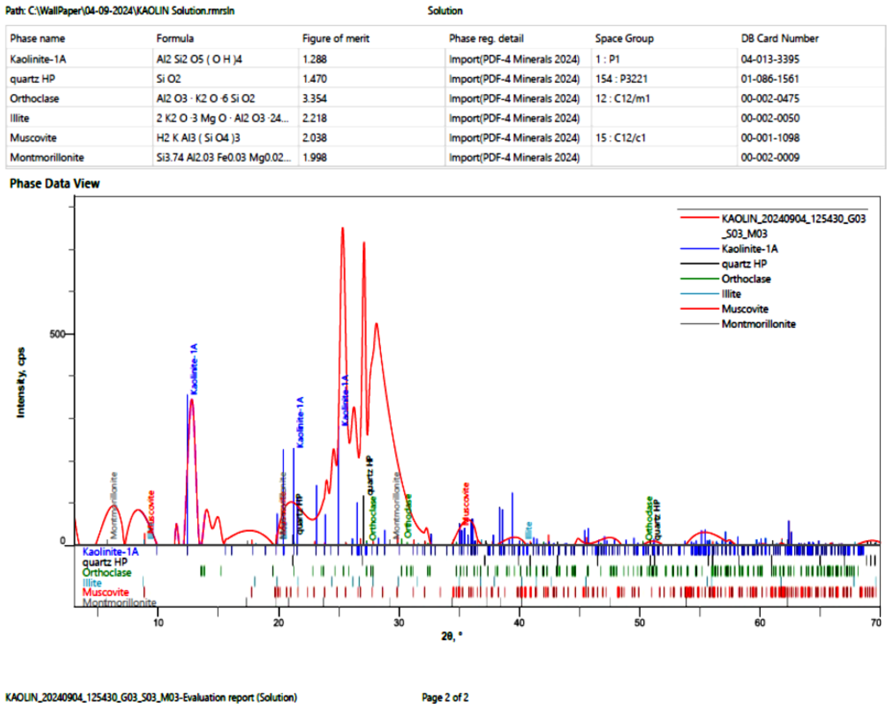
Mineral Phase	Kaolin (Weight%)	Adsorption Significance
Kaolinite-1A	36	Moderate adsorption via surface hydroxyl groups and layers.
Montmorillonite	11	Excellent adsorption; high cation exchange capacity (CEC).
Illite	13	Moderate CEC; contributes to adsorption but is less efficient.
Muscovite	7	Low adsorption; a minor role in total capacity.
Quartz HP	21	Non-adsorptive; dilutes overall adsorption capacity.
Orthoclase	11	Minimal adsorption; acts as an inert filler.

The sharp and well-defined peaks of kaolinite and montmorillonite in Kaolin (Figure 5a and b) indicate a high degree of crystallinity, suggesting a relatively ordered structure. Although high crystallinity may limit the number of defects that act as active sites, the presence of nanometric particle sizes (e.g., ~49 Å to 252 Å) enhances the specific surface area, which is crucial for adsorption. Fine particles provide greater exposure of active sites, thus improving the efficiency of adsorption processes.

The presence of non-clay minerals such as Quartz (21%) and Orthoclase (11%) in Kaolin has a diluting effect on the adsorptive potential. These minerals do not contribute significantly to adsorption due to their low surface reactivity and absence of exchangeable sites. Their presence reduces the effective surface area and lowers the number of available active sites per unit mass of material.

The mineral compositions of this Kaolin sample show that it is suitable for a range of adsorption applications, including: water and wastewater treatment (e.g., removal of heavy metals, dyes, and organic contaminants); soil remediation, where clay minerals can immobilize pollutants; and industrial effluent treatment, benefiting from cation exchange and surface adsorption mechanisms.

However, this Kaolin with 47 % non-clay minerals (Quartz and Orthoclase) may require pretreatment (e.g., beneficiation or activation) to enhance its adsorptive properties for specialized applications. Techniques such as acid activation, thermal treatment, or particle size reduction could increase surface area and improve adsorption performance.



Path: C:\WallPaper\04-09-2024\KAOLIN Solution.rmrsln

Solution

Phase name	Formula	Figure of merit	Phase reg. detail	Space Group	DB Card Number
Kaolinite-1A	Al2 Si2 O5 (O H)4	1.288	Import(PDF-4 Minerals 2024)	1 : P1	04-013-3395
quartz HP	Si O2	1.470	Import(PDF-4 Minerals 2024)	154 : P3221	01-086-1561
Orthoclase	Al2 O3 · K2 O ·6 Si O2	3.354	Import(PDF-4 Minerals 2024)	12 : C12/m1	00-002-0475
Illite	2 K2 O ·3 Mg O · Al2 O3 ·24...	2.218	Import(PDF-4 Minerals 2024)		00-002-0050
Muscovite	H2 K Al3 (Si O4)3	2.038	Import(PDF-4 Minerals 2024)	15 : C12/c1	00-001-1098
Montmorillonite	Si3.74 Al2.03 Fe0.03 Mg0.02...	1.998	Import(PDF-4 Minerals 2024)		00-002-0009

Phase Data View

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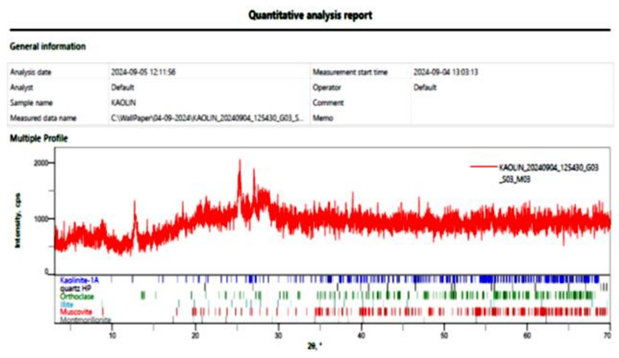
Fig. 5(a) X-Ray Diffraction (XRD) Qualitative Analysis of Kaolin


Quantitative analysis report

General information

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Analyst	Default	Operator	Default
Sample name	KAOLIN	Comment	
Measured data name	C:\WallPaper\04-09-2024\KAOLIN_20240904_125430_G03_S...	Memo	

Multiple Profile

Fig. 5(b) XRD Quantitative Analysis of Kaolin

3.2. Kaolin's Adsorption Capacity for Environmental Pollutants

The composition of the simulated wastewater before and after treatment with Kaolin at a dose of 5 g/L is tabulated in Tables 2 and 3. The treatment with Kaolin significantly improves water quality, reducing turbidity, COD, and heavy metals effectively while slightly increasing the pH.

Table 2. Simulated Wastewater Composition Before Treatment

Parameter	**Value**	**Unit**
Turbidity	300.0	NTU
COD	800.0	mg/L
Pb^{2+} (Heavy Metal)	10.0	mg/L
pH	6.50	-

Table 3. Simulated Wastewater Composition After Treatment (Kaolin Dose: 5 g/L)

Parameter	**Value**	**Unit**	**Reduction (%)**
Turbidity	24.63	NTU	91.8%
COD	178.50	mg/L	77.7%
Pb^{2+} (Heavy Metal)	1.35	mg/L	86.5%
pH	6.86	-	Slight Increase

Table 4 shows that increasing Kaolin dosage significantly reduces both turbidity and COD, following an exponential decay pattern.

Table 4. Simulated Results for Turbidity and COD Reduction with Increasing Kaolin Doses

Kaolin Dose (g/L)	**Turbidity (NTU)**	**COD (mg/L)**
0.0	300.0	800.0
0.5	233.6	688.6
1.0	181.96	592.65
2.0	110.36	439.05
3.0	66.94	325.26
4.0	40.60	240.96
5.0	24.63	178.50

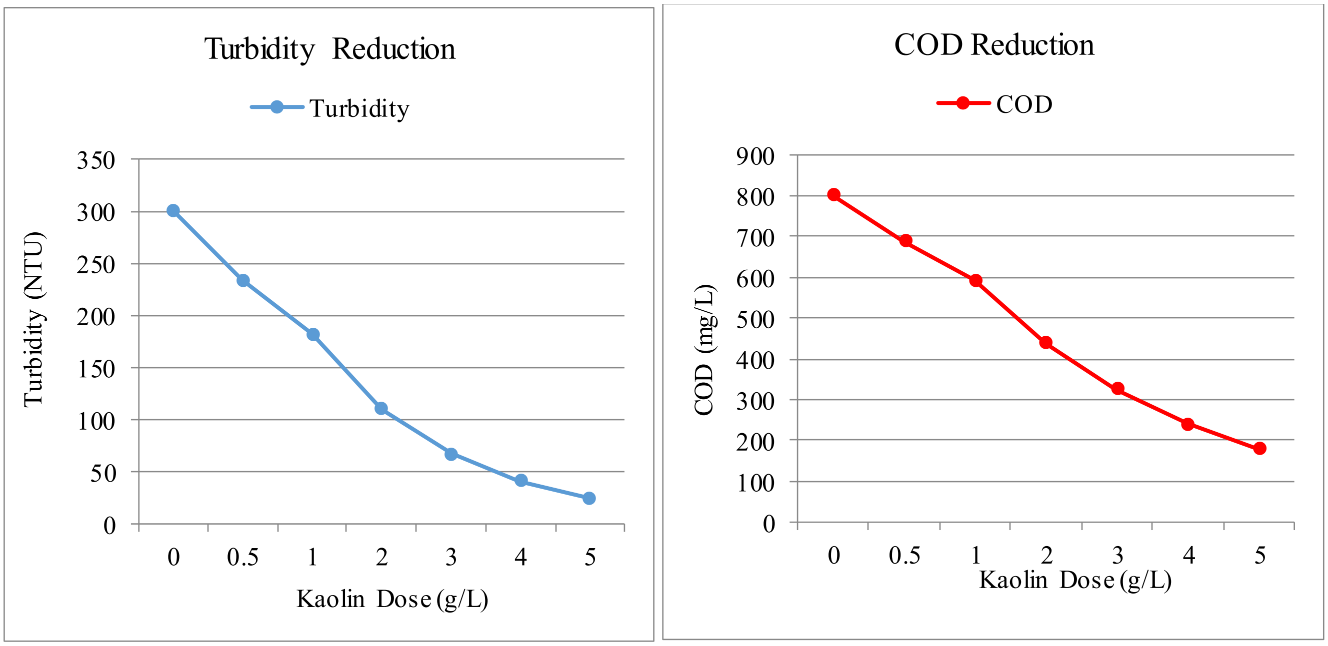

Fig. 6 Simulated Results for Turbidity and COD Reduction with Increasing Kaolin Doses

Table 5 shows the simulated results for heavy metal (Pb^{2+}) reduction and pH changes with increasing Kaolin doses. From Figure 7, it can be observed that there is a significant reduction in the heavy metal Pb^{2+} concentration, dropping by 86% at a 5 g/L Kaolin dosage. Kaolin slightly increases pH, likely due to its mild alkalinity, as shown in Figure 7.

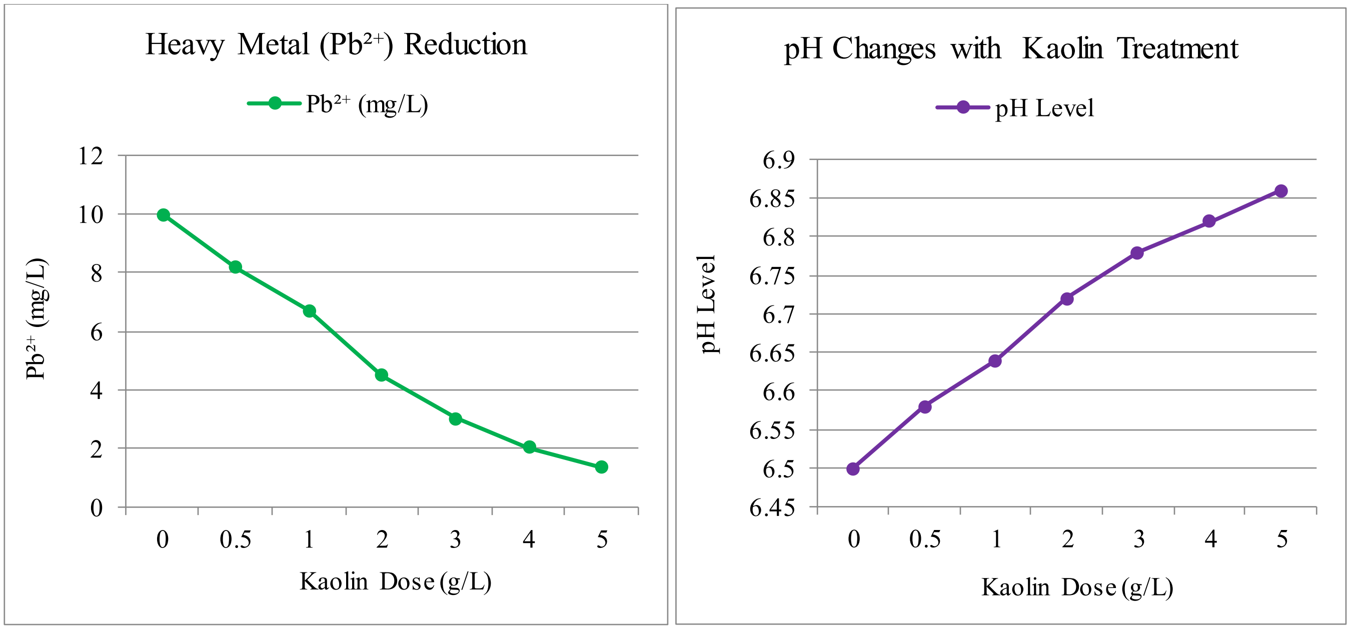

Fig. 7 Simulated Results for Heavy Metal (Pb^{2+}) Reduction and Ph Changes with Increasing Kaolin Doses

Table 5. Simulated Results for Heavy Metal (Pb^{2+}) Reduction and pH Changes with Increasing Kaolin Doses

Kaolin Dose (g/L)	Pb^{2+} (mg/L)	pH Level
0.0	10.0	6.50
0.5	8.19	6.58
1.0	6.70	6.64
2.0	4.49	6.72
3.0	3.01	6.78
4.0	2.02	6.82
5.0	1.35	6.86

3.3. Adsorption Kinetics of Kaolin in Wastewater Treatment

The adsorption process of Kaolin for pollutants (e.g., heavy metals, organic matter) follows kinetic models that describe how quickly and efficiently contaminants are removed.

3.3.1. Adsorption Kinetics of Kaolin for Pb^{2+} Removal

Using the Pseudo-Second-Order (PSO) model, the adsorption of Pb^{2+} onto Kaolin was simulated over 0 to 120 minutes. Within the first 20 minutes, over 85 % of Pb^{2+} is adsorbed.

An initial Pb^{2+} concentration of 10 mg/L was used. It was observed that there was rapid initial adsorption within the first 20 minutes, over 85 % of Pb^{2+} was adsorbed. Equilibrium was reached at 120 minutes with maximum adsorption capacity stabilizing at 7.84 mg/g.

Chemisorption dominates since the PSO model fits well, and chemical bonding (chemisorption) is the primary mechanism rather than simple physical attraction.

Table 6. The Adsorption Kinetics of Kaolin can be Analysed using the Following Models

Kinetic Model	Equation	Description
Pseudo-First-Order (PFO)	$q_t = q_e(1 - e^{-k_1 t})$	Adsorption depends on the concentration difference between the surface and the bulk solution. Suitable for physisorption.
Pseudo-Second-Order (PSO)	$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t}$	Assumes chemisorption as the rate-limiting step, with adsorption proportional to available binding sites.
Intraparticle Diffusion (IPD)	$q_t = k_1 t^{0.5} + C$	Suggests that adsorption occurs in multiple steps, including surface adsorption and diffusion inside pores.

Table 7. Adsorption Kinetics of Kaolin for Pb^{2+} Removal

Time (min)	Adsorbed Pb^{2+} (mg/g)
0.0	0.00
10.0	6.10
20.0	7.07
40.0	7.50
60.0	7.69
80.0	7.76
100.0	7.81
120.0	7.84

From Table 8 and Figure 9, it can be observed that Pseudo-Second-Order (PSO) is the best fit for Kaolin adsorption. And it suggests chemisorption (strong bonding between Kaolin and Pb^{2+}). The Pseudo-First-Order (PFO) initially closes to PSO but levels off. This suggests physisorption (weaker surface interactions). Intraparticle Diffusion (IPD) fits well in later stages, meaning diffusion inside Kaolin pores plays a role. However, the non-zero intercept ($C \neq 0$) suggests surface adsorption is also involved.

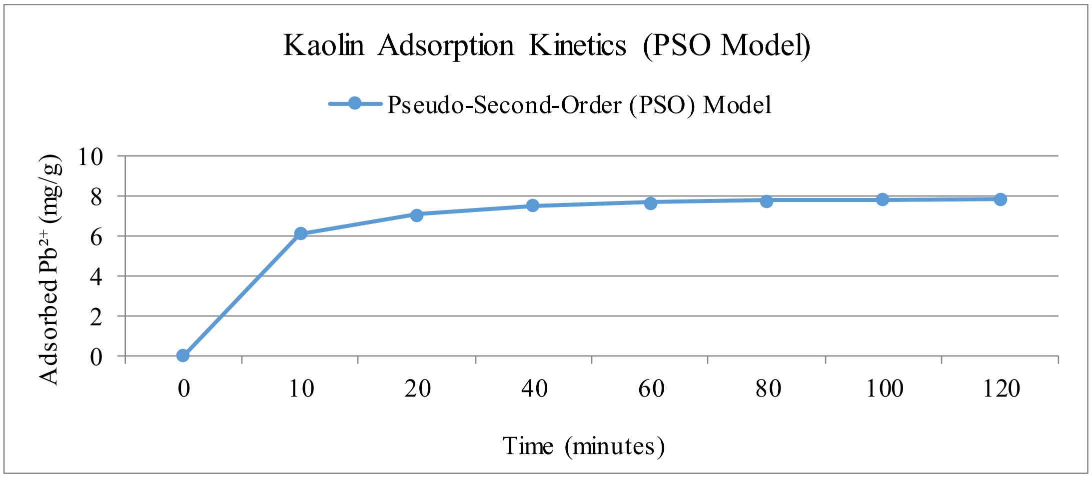

Fig. 8 Adsorption Kinetics of Kaolin for Pb^{2+} Removal

Table 8. Comparison of Adsorption Kinetics Models for Kaolin in Pb^{2+} Removal

Time (min)	PSO (mg/g)	PFO (mg/g)	IPD (mg/g)
0.0	0.00	0.00	1.50
10.0	6.10	4.80	4.00
20.0	7.07	6.80	5.00
40.0	7.50	7.82	6.42
60.0	7.69	7.97	7.53
80.0	7.76	7.99	8.75
100.0	7.81	8.00	9.54
120.0	7.84	8.00	10.26

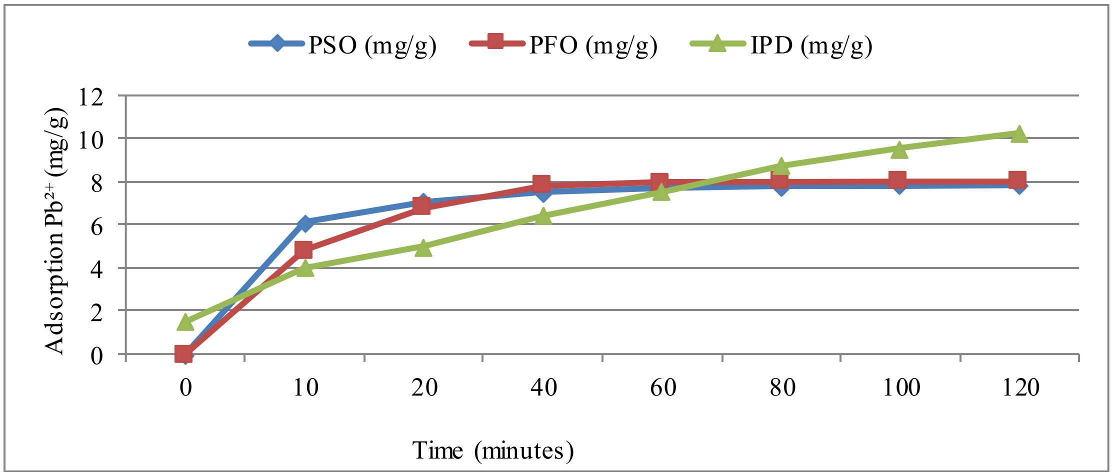

Fig. 9 Comparison of Adsorption Kinetics Models for Kaolin in Pb^{2+} Removal

4. Conclusion

This study confirms that unmodified Kaolin is a sustainable, low-cost, and environmentally benign adsorbent capable of effectively removing heavy metals, turbidity, and organic pollutants such as COD from wastewater. Its adsorptive performance is primarily attributed to its inherent clay mineral composition, notably the presence of Kaolinite and Montmorillonite. However, the presence of non-adsorptive mineral phases may partially inhibit overall adsorption efficiency. To enhance performance, further material refinement, such as purification, surface functionalization, or nanocomposite formation, should be explored to increase selectivity, adsorption capacity, and reusability.

Kinetic modelling results indicate that the Pseudo-Second-Order (PSO) model best describes the adsorption behaviour, supporting chemisorption as the dominant mechanism. The Pseudo-First-Order (PFO) model, although partially applicable, underestimates adsorption at equilibrium. Intraparticle Diffusion (IPD) analysis further reveals a two-stage adsorption process: rapid surface adsorption followed by slower pore diffusion. Kaolin's stable performance under neutral pH conditions makes it particularly suitable for pH-sensitive applications where chemical coagulants like alum or ferric chloride may pose limitations. Given its minimal impact on solution pH, combined with high removal efficiencies and thermal stability, Kaolin represents a promising candidate for decentralized and large-scale wastewater treatment systems. Pilot-scale studies are recommended to validate its real-world applicability and long-term operational performance. Overall, this study supports the broader adoption of raw Kaolin as a green and economical alternative for integrated water treatment solutions in both environmental and industrial settings.

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