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# Treatment of Glyphosate-Contaminated Water for Sustainable Environmental Management

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## Abstract

The natural environment is defined as the entirety of the Earth's natural components and has been increasingly impacted by human activities in recent decades. Agricultural intensification, particularly in Algeria, has led to a substantial increase in the use of fertilizers and phytosanitary products to improve crop yield and quality. Among these products, glyphosate is the most widely used herbicide for weed control due to its effectiveness against annual, biennial, and perennial plants. This study investigates the removal of glyphosate from contaminated water using an abundant natural material, sodium-modified clay. Physicochemical characterizations were carried out to identify the surface functional groups and charge properties of the adsorbent. Adsorption experiments demonstrated that a clay mass of 0.1 g removed approximately 60% of glyphosate within 20 min at pH 5. Kinetic analysis showed that the adsorption process follows a pseudo-second-order model. Adsorption isotherm studies were conducted to elucidate the adsorption mechanism. The experimental data fitted well with the Langmuir, Temkin, and Dubinin–Radushkevich models, indicating monolayer adsorption with a maximum adsorption capacity of 18.18 mg $g^{-1}$. These results highlight the potential of sodium clay as an efficient, low-cost adsorbent for glyphosate removal from contaminated water.

**Keywords:** Environment, Agronomy, adsorption, herbicide, Clay.

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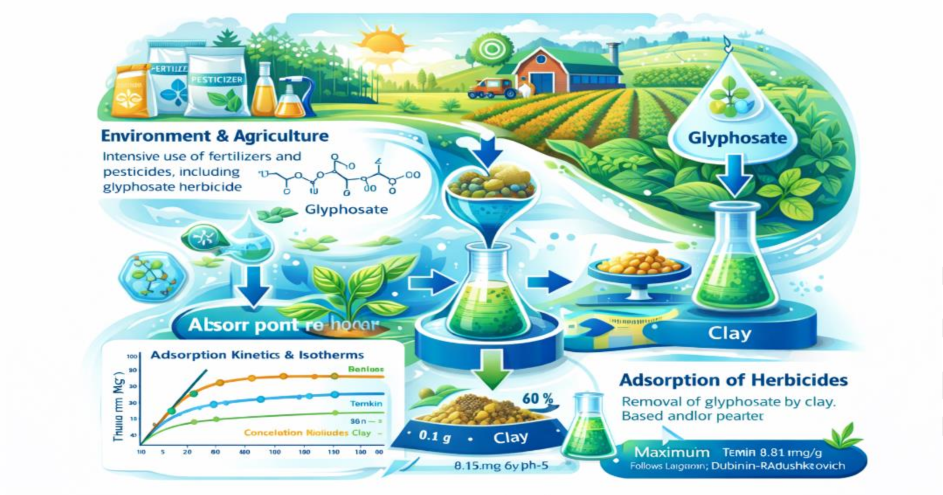
## Graphical abstract



## 1. Introduction

Environmental pollution, particularly the contamination of water resources by chemical substances, has become one of the most pressing global challenges of the twenty-first century. Rapid industrialization, intensified agricultural practices (Altenor *et al.*, 2009; Baghdadi *et al.*, 2017; Elaziouti *et al.*, 2011; Amari *et al.*, 2018), and demographic growth have significantly increased the release of hazardous compounds into aquatic environments (Al-Muhtase *et al.*, 2011; Ugurlu *et al.*, 2011; Gong *et al.*, 2011; Maldonado *et al.*, 2006). Water, an essential resource for human life, food production, and economic development, is increasingly exposed to degradation due to anthropogenic activities (Aysegul *et al.*, 2013). Among the various sources of contamination, agricultural runoff represents a major contributor to diffuse pollution, especially through the widespread use of pesticides and herbicides (Lunhong *et al.*, 2011; Barka *et al.*, 2008; Zhang *et al.*, 2013). Herbicides are extensively applied worldwide to enhance agricultural productivity by controlling weeds and protecting crops. However, their intensive and sometimes uncontrolled use has led to serious environmental and health concerns (Mansour *et al.*, 2011; Omer *et al.*, 2018; Khan *et al.*, 2019; Medjdoubi *et al.*, 2019). Once introduced into the environment, these compounds can persist in soil and migrate into surface and groundwater systems through leaching and runoff processes. Even at low concentrations, the presence of herbicides in water bodies may pose risks to aquatic ecosystems and human health (Zhang *et al.*, 2013; Altenor *et al.*, 2009).

Glyphosate (N-(phosphonomethyl)glycine) is one of the most widely used non-selective herbicides globally. It is employed in a variety of agricultural systems, including cereal crops, orchards, vineyards, and vegetable production, as well as in non-agricultural settings. Despite its effectiveness in weed control, glyphosate has become a subject of intense scientific debate due to its potential toxicity and environmental persistence (Bentahar *et al.*, 2018; Hu *et al.*, 2018; Boukhemkhem *et al.*, 2017). Several studies have reported its detection in rivers, groundwater, and even drinking water sources. Moreover, its classification as a probable carcinogenic compound by international agencies has heightened public and regulatory concern. As a consequence, the development of efficient and economically viable methods for glyphosate removal from contaminated water has become a priority in environmental research (Mouni *et al.*, 2018; Ngulube *et al.*, 2017; Sarma *et al.*, 2011). Various physical, chemical, and biological treatment technologies have been proposed to reduce pesticide concentrations in wastewater, including advanced oxidation processes, membrane filtration, biodegradation, and coagulation–flocculation techniques (Kausar *et al.*, 2018; Şahin *et al.*, 2015). Among these methods, adsorption has emerged as one of the most effective and widely applied approaches due to its operational simplicity, high removal efficiency, and relatively low cost. Recent studies have reported the effective removal of glyphosate using natural and modified clay materials, highlighting the importance of adsorption mechanisms and surface interactions (Magda *et al.*, 2026; Osama *et al.*, 2022; Sabrina *et al.*, 2022; Sabiha *et al.*, 2025). The principle of adsorption is based on the accumulation of pollutant molecules onto the surface of a solid material, known as an adsorbent, through physical or chemical interactions. Activated carbon is traditionally considered one of the most efficient adsorbents; however, its relatively high cost and regeneration requirements limit its large-scale application, particularly in developing regions. Consequently, increasing attention has been directed toward low-cost and naturally abundant materials. Natural clays have attracted significant interest in this context due to their availability, environmental compatibility, and favorable physicochemical properties.

In particular, sodium-rich smectitic clays are widely distributed across many regions of the world and exhibit similar structural and surface characteristics. These clays are characterized by a layered structure, high specific surface area, notable swelling capacity, and substantial cation exchange capacity. Their negatively charged surfaces and exchangeable interlayer cations enable various interaction mechanisms with ionic and polar contaminants. Such intrinsic properties make sodium smectitic clays promising candidates for the adsorption of herbicides such as glyphosate, which possesses multiple functional groups capable of participating in electrostatic interactions, hydrogen bonding, and surface complexation reactions.

Although numerous studies have investigated the adsorption of pesticides onto different materials, including activated carbon, zeolites, and modified biomaterials, the adsorption behavior of glyphosate onto sodium-rich natural smectitic clays remains insufficiently explored in a comprehensive manner. Existing works often focus on removal efficiency without providing an integrated mechanistic analysis combining adsorption kinetics, equilibrium modeling, and systematic evaluation of operational parameters. Furthermore, while some studies have examined specific clay samples, the broader applicability of findings to widely distributed clay categories have not always been clearly emphasized. It is important to underline that sodium smectitic clays are not restricted to a single geographical location. They belong to a mineralogical family that is globally available and shares comparable physicochemical characteristics across different regions. Therefore, investigating the adsorption behavior of a locally sourced sodium clay provides insights that are transferable to similar materials worldwide. The adsorption mechanisms governing glyphosate removal are primarily determined by the structural and chemical properties of the clay mineral rather than by its geographical origin. Understanding these mechanisms is essential for designing efficient and sustainable water treatment strategies. In this context, the present study aims to investigate the adsorption performance of a sodium natural clay toward glyphosate removal from aqueous solutions. Although the clay sample used in this work was locally collected, it is representative of a widely distributed smectitic clay family, thereby ensuring the broader relevance of the results. The study focuses on enhancing adsorption performance through a simple and cost-effective pretreatment method, making the approach practical and economically feasible. The proposed treatment process is designed as a pre-irrigation remediation step, intended to improve the quality of contaminated groundwater before its agricultural use, thereby reducing environmental and food-chain transfer risks.

A comprehensive parametric investigation was conducted to evaluate the influence of key operational variables, including contact time, adsorbent dosage, pH of the solution, and initial glyphosate concentration. Adsorption kinetics were analyzed using pseudo-first-order and pseudo-second-order models, as well as the intraparticle diffusion model, to identify the rate-controlling mechanisms. In addition, equilibrium data were interpreted through isotherm models in order to elucidate the adsorption behavior and determine the interaction characteristics between glyphosate molecules and the clay surface. By integrating kinetic modeling, equilibrium analysis, and operational parameter optimization, this work provides a detailed mechanistic understanding of glyphosate adsorption onto sodium smectitic clays. The originality of the study lies in the combination of a low-cost enhancement strategy with a comprehensive analytical approach applied to a clay type that is globally distributed. The findings contribute to advancing knowledge on glyphosate–clay interactions and support the development of sustainable, accessible, and scalable water treatment solutions beyond a strictly local framework. The originality of this study lies in the combination of a low-cost and easily applicable pretreatment strategy with a comprehensive mechanistic analysis of glyphosate adsorption onto a widely available sodium smectitic clay. This approach provides both fundamental insights and practical relevance for sustainable water treatment applications.

## 2. Experimental

### 2.1. *Materials*

The adsorbent used is bentonite coming from the deposit of ghoussel "Hammam Boughrara," located in the west of Algeria. To improve its adsorption capacity, we subjected the bentonite to a chemical treatment. This operation consists in removing the impurities found in the clay, such as organic matter, iron sulfides formed, and aluminum hydroxides and oxides. The clay is chemically treated with HCl (0.5M) and hydrogen peroxide ($H_2O_2$). After each operation, the clay pellet is filtered and then washed until the total elimination of chlorides (silver nitrate test). Then we proceed to the saturation with sodium, carried out to ensure homogenization of the clay. This is done by exchange with a solution of NaCl (1N). The operation is repeated 3 times with distilled water and then a wash until the supernatant does not contain any chlorides.

### 2.2. *Adsorbate*

Glyphosate N-(phosphonomethyl) Glycine is a synthetic molecule, a weak organic acid analog of a natural amino acid, absorbed by the leaves. It is very soluble in water and very polar and soluble in most organic solvents (Organisation mondiale de la santé (OMS), 2025) (Figure 1).

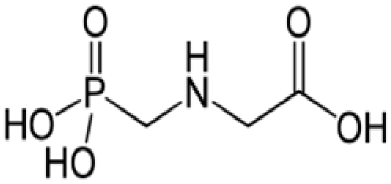


**Figure 1**. The molecule of Glyphosate.

### 2.3. *Instruments*

Fourier transform infrared (FTIR) spectroscopy was performed using a PerkinElmer ALPHA Bruker spectrometer equipped with an attenuated total reflectance (ATR) diamond crystal. Spectra were recorded over the wavenumber range of 4000–400 cm$^{-1}$ in order to identify the surface functional groups and chemical structure of the adsorbent material. The mineralogical composition and crystalline structure of the clay were analyzed by X-ray diffraction (XRD) using a Philips Analytical X'PERT Pro diffractometer with Cu Kα radiation (λ = 1.5418 Å), operating at 45 kV and 40 mA. The data were collected over an appropriate 2θ range with a scanning time of 10–20 minutes. The point of zero charge ($pH_{pzc}$) of the adsorbent was determined using the pH drift method, as described in previous work (Imene *et al.*, 2019), in order to evaluate the surface charge properties of the material.

### 2.4. *Adsorption study*

All experiments are done at room temperature (25°C); the protocol is as follows: A known mass of clay is suspended in a known volume of a solution of glyphosate at the desired concentration; the suspensions are then shaken and then filtered; the glyphosate remaining in equilibrium is analyzed by UV-visible spectrometry. Concerning our work, we have realized first the influence of various experimental parameters, then the adsorption kinetics to determine the adsorption mechanism between the support and the glyphosate solution at equilibrium. All experiments were performed in triplicate, and the results are expressed as mean ± standard deviation (SD).The adsorbed quantities are calculated using the following equation:

$$Q_{ads} = \frac{C_0 - C_{eq}}{m} . V \qquad (1)$$

And the percentage of discoloration is calculated as follows:

$$P(\%) = \frac{C_0 - C_{eq}}{C_0} \cdot 100 \qquad (2)$$

With: Qads: Adsorbed quality by a gram of the adsorbent in (mg/g), C0: initial concentration in (mg/L), Ceq: concentration at equilibrium in (mg/L), V: Solution volume in (L), m: Adsorbent mass in (g), P (%): Percentage of discoloration.

The results obtained from the protocols followed in the laboratory are given in curves for each parameter: the contact time, the pH of the solution, the mass of clay in the solution, and the influence of the initial concentration. Statistical analysis was performed using one-way ANOVA at a 95% confidence level ($p < 0.05$). All experiments were conducted in triplicate.

## 3. Results and discussion

### 3.1. *Characterization of the materials*

According to the table of infrared spectroscopy, For the spectrum of glyphosate (Figure 2), we observe a band located at 3242 cm$^{-1}$; this band is attributed to the vibration of elongation of the OH bond. And the band located at 1621 cm$^{-1}$ corresponds to the elongation of the bond C=O. The band located at 1396 cm$^{-1}$ corresponds to a deformation in the OH bond plane. The band located at 1322 cm$^{-1}$ is attributed to the C-N amine function, and the band located at 1166 cm$^{-1}$ is due to the $CO_2H$ acid bond. And lastly, the band is located at 1073 cm$^{-1}$, which is due to the elongation of the N-H bond. For the FTIR spectrum concerning the sodium clay (Figure 3), an intense band located between 900 and 1200, centered around 1040 cm$^{-1}$, corresponds to the valence vibrations of the Si-O bond. The bands located at 525, 466, and 422 cm$^{-1}$ are attributed, respectively, to the deformation vibrations of Si-O-Al bonds and Si-O-Mg and Si-O-Fe bonds. Also, characteristic bands of Al-OH deformation vibrations appear between 770 and 800 cm$^{-1}$. The sharing of the OH group between Fe and Al atoms in octahedral position can shift the Al-OH vibrations to about 680 and 794 cm$^{-1}$. The Mg-O and Mg-OH vibrations (confused with Si-O) are located at 515 and 490 cm$^{-1}$, respectively. The band located at 3415 cm$^{-1}$ is due to the elongation of the OH bond, and the band located at 1622 cm$^{-1}$ is attributed to the elongation of the C=O bond.

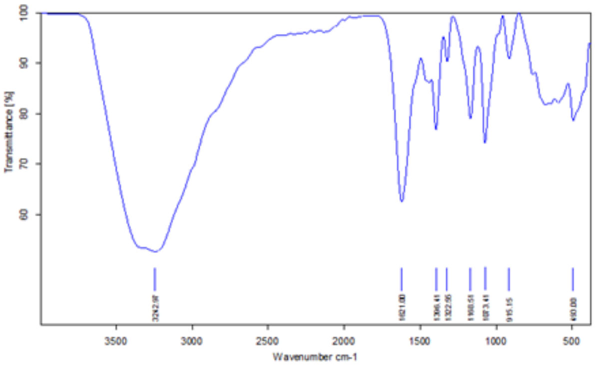


**Figure 2.** FTIR spectra of glyphosate.

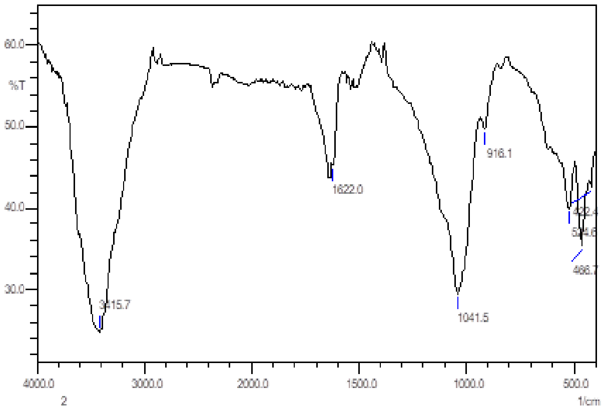


**Figure 3.** FTIR spectra of sodium clay.

XRD examination confirms the good purification of the clay since impurities such as quartz (3.88 Å), calcite (3.68 Å), and cristobalite 3.50 Å are largely eliminated during purification (Figure 4). We also note that there is an increase in the basal distance for the clay; it goes from 11.24 Å for the raw clay (CC) to 13.05 Å for the sodium clay (SC).

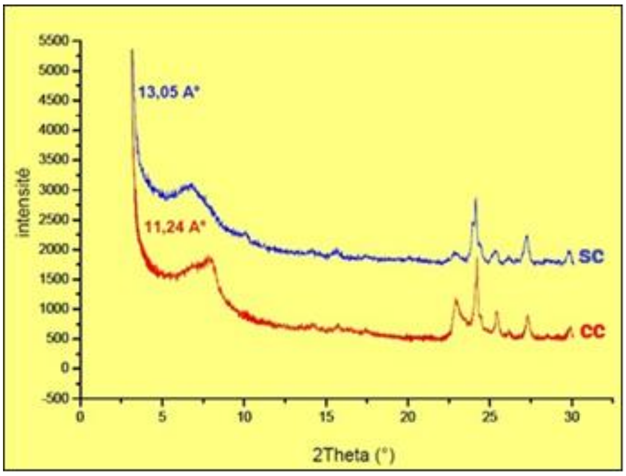


**Figure 4** . Diffractroramm of raw and sodium clays.

The specific surface of raw and sodium clay is 42 m²/g and 96 m²/g, respectively, which confirms the good purification of our clay. The pHZPC value for sodium clay is 5.11; i.e., for pH values above pHZPC, the surface of our material is negatively charged, and for pH values below pHZPC, the surface is positively charged (Guiza el al. 2013, Youcef *et al.* 2006, Benguella el al. 2006).

## 3.2. *Adsorption of glyphosate*

### *3.2.1. Effect of contact time*

The first test was performed with a concentration of 10 g/L under agitation at different times. The result of this test is represented in this case graphically by the percentage of discoloration as a function of contact time (Figure 5).

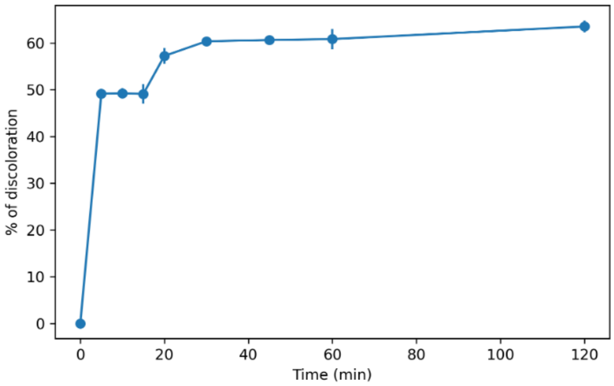


**Figure 5.** Effect of contact time on glyphosate removal efficiency using sodium natural clay. Error bars represent ± standard deviation of triplicate experiments.

Figure 5 shows a rapid increase in the elimination of glyphosate on the sodium clay with increasing contact time. Elimination of the herbicide was observed from the first time; after a sufficient contact time of 20 min, the residual concentration of glyphosate in the aqueous phase decreased. As shown in Figure 1, the discoloration efficiency increased rapidly during the first 20 min, reaching 57.23 ± 1.63%. After 30 min, the process reached a plateau around 60%, indicating that equilibrium was achieved. This elimination is very fast at the first contact because of the availability of the active sites in our adsorbent. The rate of adsorption becomes stable after 20 min of agitation and reaches the equilibrium with a rate of 60%. This equilibrium is due to the saturation of the majority of the sites by the glyphosate. One-way ANOVA confirmed that contact time had a statistically significant effect on glyphosate removal efficiency ($p < 0.05$), indicating that the observed differences between contact times are not due to random variation but reflect a true adsorption trend.

### *3.2.2. Effect of pH solution*

The pH is an important factor in any adsorption study; it allows us to have and choose the best pH conditions for a charged molecule removal study and thus to minimize the number of experiments for a better adsorption capacity. In addition, to study the influence of pH on the adsorption of glyphosate on sodium montmorillonite, we prepared a solution of glyphosate with a concentration of 10 mg/L (the initial pH of the solution is 5). We then varied the pH of this solution between 2 and 10 using solutions of HCl and NaOH.

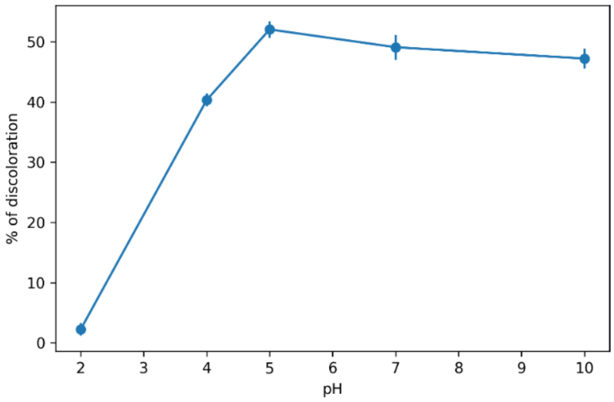


**Figure 6.** Effect of the pH on glyphosate adsorption onto sodium clay. Error bars represent ± standard deviation of triplicate experiments. Error bars represent the standard deviation of three independent experiments (n = 3).

Figure 6 shows the effect of the pH of the solution on the adsorption capacity of glyphosate on sodium clay. It was found that the percentage of adsorption increased significantly with increasing pH until reaching a maximum (62%) at pH = 5 (initial pH of the solution of glyphosate). Figure 6 shows the effect of pH on discoloration efficiency. The removal efficiency increased from acidic pH to reach a maximum at pH 5 (52.07 ± 1.38%), followed by a slight decrease at higher pH values. This result is confirmed by the study of pHZPC. At pH < pHZPC, the surface of the adsorbent is positively charged, which produces an attraction of the positively charged sites of the clay with the basic functions of glyphosate. The optimum pH is 5. ANOVA analysis confirmed that the differences in adsorption capacity between the different pH levels were statistically significant ($p < 0.05$).

### *3.2.3. Influence of the adsorbent mass*

Subsequently, the effect of adsorbent mass on the adsorption of glyphosate on sodium clay was tested; the result is shown in Figure 7.

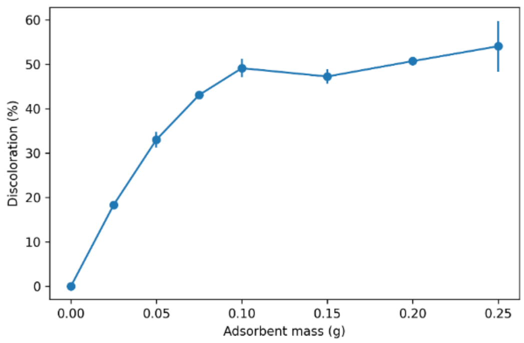


**Figure 7.** Effect of the adsorbent mass on glyphosate adsorption. Error bars represent ± standard deviation of triplicate experiments.

The result presented in figure 7 shows that the adsorption rate of glyphosate increases from 18% to 52%; this is due to the presence of more active sites on the surface of the clay. The initial rapid increase is due to the availability of a larger surface area of the adsorbent, but a further increase in clay saturates the surface of the adsorbent, and equilibrium is reached. As shown in Figure 7. A mass of clay of 0.1 g is required to bind the maximum of glyphosate. Analysis of variance (ANOVA) confirmed that the differences in adsorption capacity between the different masses were statistically significant ($p < 0.05$). Similar statistically significant effects were observed for adsorbent dose and contact time. The error bars in Figures 5, 6 and 7 represent the standard deviation (±) calculated from three experiments performed in triplicate.

### 3.3. *Isotherm study*

This test concerns the effect of concentration on the adsorption of glyphosate on sodium montmorillonite; the results are shown in figure 8.

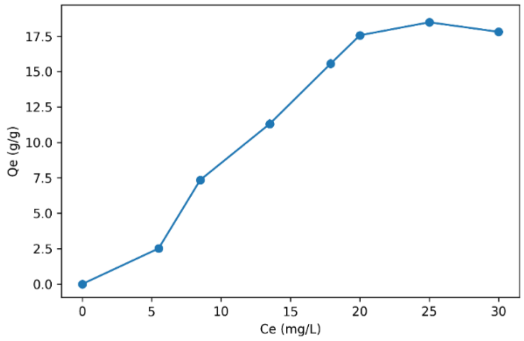


**Figure 8.** Adsorption isotherm of glyphosate onto sodium clay. Error bars represent the standard deviation of three independent experiments (n = 3).

The plot of the figure above shows that the adsorption capacity increases with the increase of the initial concentration. The isotherm presents an equilibrium level indicating the saturation of the surface sites and thus the formation of a monolayer. Sodium montmorillonite has an adsorption capacity of 18.18 g/g.

#### *3.3.1. Modeling of adsorption isotherms*

To better understand the adsorption process of glyphosate by sodium clay, the adsorption isotherm data were analyzed based on several mathematical models widely used in the literature; the linear forms of the models used are given in **Table 1** (Mekatel *et al.* 2015, Rytwo *et al.* 2010, Chen *et al.* 2022).

According to the results presented in table 2, the adsorption of glyphosate on sodium clay follows the Langmuir model with $R^2$ higher than 0.9 and qexp and qm close to each other; the value of RL is within the range of validity, confirming that the adsorption is favorable and takes place in a monolayer. Temkin's model indicates that the adsorption of glyphosate on sodium clay is chemisorption ($R^2 > 0.9$). The Dubini-Radushkevich model allows us to calculate the average free energy E, defined as the change of free energy when 1 mole of ion is transferred towards the surface of the solid (if E < 8 kJ/mol, it is a chemisorption, and if E > 8 kJ/mol, the adsorption is physical). In our case, E kJ/mol confirms the chemical nature of the adsorption of the glyphosate on the sodium clay.

### 3.4. *Kinetic study*

In this part, different models of adsorption kinetics were tested to elucidate the mechanism of adsorption in these microparticles. The models used in this study are the kinetics of the pseudo-first-order (eq3) and second-order (eq4) as well as the intraparticle diffusion (eq5). These mathematical models were chosen on the one hand for their simplicity and on the other hand for their application in the field of adsorption of organic compounds on the various adsorbents.

$$\ln(qe-qt)=\ln qe-k1t \quad (3)$$

$$\frac{t}{qt}=\frac{1}{K_2qe^2}+\frac{t}{qe} \quad (4)$$

$$qt=kintt1/2+C \quad (5)$$

Where Qe is the quantity of the adsorbed coloring in the equilibrium time (mg/g), Qt is the quantity of the adsorbed coloring in the time t (mg/g), $K_1$ is the speed constant of the first class ($\text{min}^{-1}$), $K_2$ is the constant of the second-order speed (g/mg min), and h = $K_2$. $q_{e2}$, the initial diffusion speed (mg/g min), C: ordinate originally, Kint: the speed constant of intraparticle diffusion.

After analyzing the modeling results mentioned in the table below, we can conclude that the most representative model of the adsorption kinetics is the second-order model, where the coefficient of determination is 0.999, thus rapid adsorption. The pseudo-second-order model reveals that adsorption is chemical and that adsorption depends on the adsorbent-adsorbate couple. We can therefore conclude that the interaction between glyphosate and sodium clay occurs either by charge neutralization or by electrostatic attraction. In conclusion, we can say that the adsorption of glyphosate on sodium clay follows the pseudo-second-order model with intraparticle diffusion (Medjdoubi *et al.* 2019, Mouni *et al.* 2018).

It is important to note that, in real wastewater systems, the presence of co-existing pollutants such as other pesticides, heavy metal ions, and dissolved organic matter may influence glyphosate adsorption behavior. These species can compete with glyphosate for active adsorption sites, reduce adsorption efficiency through site blockage, or alter the surface properties of the adsorbent. In particular, dissolved organic matter may form complexes with glyphosate or occupy adsorption sites, thereby limiting its removal. Although the present study was conducted under controlled conditions using model aqueous solutions to better understand the adsorption mechanisms, these results provide a fundamental basis for predicting behavior in more complex systems. Further studies involving real wastewater matrices are necessary to fully evaluate the performance of the proposed adsorbent under practical conditions.

**Table 1.** Linear forms of the isotherm models used.

| Models | Equation | Parameters |
|---|---|---|
| Freundlich | $\mathrm{Ln}\, q_e = \ln K_F + \frac{1}{n} \ln C_e$ | $q_e$: quantity of solute adsorbed per unit mass of adsorbent at equilibrium (mg/g). |
| | | $K_F$: Freundlich constant associated with the adsorption capacity. |
| | | Ce is the equilibrium concentration (mg/L) |
| Langmuir | $\frac{1}{q_e} = \frac{1}{C_e} \frac{1}{q_m K_L} + \frac{1}{q_m}$ | $q_m$: represents the maximum adsorption capacity (mg/g). |
| | | $K_L$: equilibrium constant, equal to the ratio of adsorption and desorption rates (L/mg). |
| Temkin | $Q_e = B_T \ln K_t + B_T \ln C_e$ | $K_T$ and $B_T$: Temkin findings |
| | $B_T \frac{Q_m.RT}{\Delta Q}$ | Θ: the recovery rate |
| Elovich | $q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t$ | t : the time (min) |
| | | $K_E$ : the equilibrium constant of Elovich (L/mg). |
| | | $\alpha$, $\beta$ elovich constants |
| Dubini – Radushkevich | $\ln Q_e = \ln Q_{mDR} - K_{D.} \mathcal{E}^2$ | **Ɛ :** filling rate |
| | $\varepsilon = RT \ln\left(\frac{1}{1+C_e}\right)$ | **$K_D$ :** constant Dubinin-Radushkevich |
| | $E = \frac{1}{\sqrt{2\mathbf{KD}}}$ | free energy |

**Table 2.** Values of the parameters of the different equations studied.

| Models | Constants | Values |
|---|---|---|
| Freundlich | $R^2$ | 0.876 |
| | 1/n | 0.220 |
| | $K_F(mg.g^{-1})(L.mg^{-1})$ | 2.34 |
| Langmuir | $R^2$ | 0.938 |
| | $q_m(mg.g^{-1})$ | 18.18 |
| | $K_L(L.mg^{-1})$ | 0.27 |
| | $R_L$ | 0.543 |
| Temkin | $R^2$ | 0.926 |
| | $K_T(L.mg^{-1})$ | 4.22 |
| | $B_T(L.mg^{-1})$ | 3.939 |
| Elovich | $R^2$ | 0.527 |
| | $q_m(mg.g^{-1})$ | 38.46 |
| | $K_T(L.mg^{-1})$ | 0.027 |
| Dubini – Radushkevich | $R^2$ | 0.969 |
| | $K_D(mol^2.J^2)$ | $6*10^{-6}$ |
| | $QmDR(mg.g^{-1})$ | 16.91 |
| | E(KJ/mol) | 0.00917 |

**Table 3.** Kinetic parameters of glyphosate adsorption on sodium clay

| Adsorbent | Pseudo Premier Order | | | Pseudo second Order | | | Diffusion Intraparticulaire | | |
|---|---|---|---|---|---|---|---|---|---|
| Sodium Clay | Qe (mg/g) | $K_1$ (min$^{-1}$) | $R^2$ | Qe (mg/g) | $K_2$ ((g mg-1.min$^{-1}$) | $R^2$ | $K_{diff}$ (mg.g-1.min-$^{1/2}$) | C | $R^2$ |
| | 06.61 | -0.0006 | 0.855 | 3.41 | 0.1 | 0.999 | 0.312 | 9.35 | 0.914 |

## 4. Glyphosate adsorption mechanism

The adsorption mechanism of glyphosate onto sodium clay is primarily governed by electrostatic interactions and hydrogen bonding (Figure 9). Under acidic to neutral pH conditions, glyphosate predominantly exists in an anionic form, which favors electrostatic attraction with positively charged sites and exchangeable sodium ions on the clay surface. Hydrogen bonding may also occur between the silanol (Si–OH) groups of montmorillonite and the functional groups of glyphosate, particularly the phosphonate and carboxylate groups. Furthermore, intraparticle diffusion plays a role in the adsorption process by facilitating the migration of glyphosate molecules into the interlayer spaces of the clay. These combined interactions lead to a stable monolayer adsorption mechanism, in agreement with Langmuir-type isotherm behavior (Yudha el al. 2025).

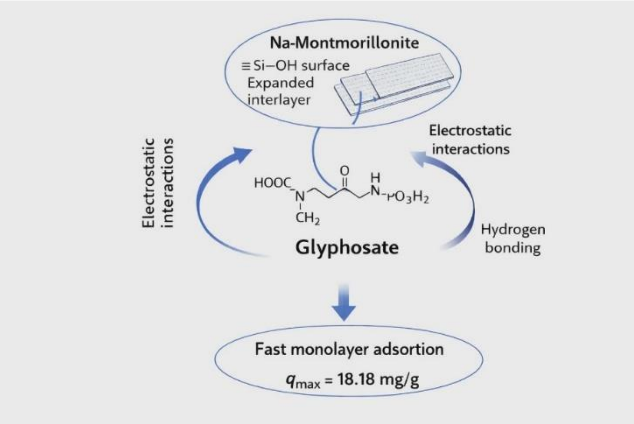


**Figure 9.** Mechanism of glyphosate removal by sodium clay

## 5. Conclusion

This study had the objective, of the use of a natural material abundant in our country: the clay chemically modified to increase its capacity of adsorption for the elimination of a herbicide very used in Algeria: the glyphosate remaining in the agricultural wastewater. The physicochemical analyses on the sodium clay showed the increase of the specific surface by the method of BET from 42m2/g before treatment to 96m2/g for the sodium clay, the good insertion of sodium was also confirmed by the increase of the basal distance from 11,24 Å to 13,05 Å. The adsorption process took place through an interaction between the silanol groups of the montmorillonite and the studied herbicide, this adsorption is influenced by the pH of the solution. The experimental results confirmed that the sodium clay has an affinity towards glyphosate, after optimization of the parameters influencing the adsorption, the maximum adsorption capacity is 18.18 mg/g and is done in monolayer, and the kinetic study revealed that the adsorption is fast of order 2 with an intraparticle diffusion. Due to the vast availability of clays in our country and the simplicity of processing, it is expected to have a significant impact on the fate of herbicides in the environment. Although the proposed approach does not introduce a novel adsorption material, it offers a practical and scalable solution based on naturally abundant resources, combined with a detailed understanding of adsorption mechanisms, which is essential for real-world water treatment applications.

### Declaration of competing interest

The authors declare that they have no conflict of interest.

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