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Research Article

Sustainable Application of Laterite for Nitrate and Sulphate Reduction in Domestic Wastewater: Adsorption Isotherm, Kinetic, and Mechanistic Studies

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Abstract
Wastewater from domestic sources, which contains nutrients such as nitrate (NO_3^-) and sulphate (SO_4^{2-}), poses serious threats to groundwater, aquatic ecosystems, and human health, particularly in rapidly growing areas where wastewater treatment facilities are limited. In resource-constrained regions, conventional wastewater treatment technologies are often expensive and difficult to implement. Although natural adsorbents have attracted considerable attention as sustainable alternatives, limited research has investigated the use of laterite blocks for the removal of nitrogen compounds from domestic wastewater. This study evaluated the potential of laterite blocks as a sustainable, low-cost, and locally available treatment medium for domestic wastewater remediation, with a particular focus on the removal of nitrate and sulphate using laterite-based filtration blocks. Batch-scale and continuous-flow experiments were conducted using municipal wastewater, and the adsorption behaviour was analysed using adsorption isotherm and kinetic models. To elucidate the adsorption mechanism, changes in surface morphology before and after adsorption were characterized using scanning electron microscopy (SEM). The results showed that the Langmuir isotherm model ($R^2 = 0.9858$) provided a better fit for nitrate adsorption than the Freundlich model ($R^2 = 0.9627$). Similarly, sulphate adsorption was better described by the Langmuir isotherm ($R^2 = 0.9930$) than the Freundlich model ($R^2 = 0.9580$), indicating that adsorption predominantly occurred as monolayer adsorption on the laterite surface. The adsorption kinetics followed the pseudo-second-order model, suggesting that chemisorption was the dominant mechanism governing the removal process. Sulphate ions interacted with the Fe and Al oxides present in the laterite through surface complexation reactions involving ligand exchange within the adsorbed layer. SEM observations further confirmed pore filling and changes in surface morphology after adsorption, demonstrating the effective accumulation of adsorbate on the laterite surface. The findings demonstrate that laterite block filtration systems can effectively remove sulphate and nitrate from domestic wastewater, highlighting their potential as a cost-effective and sustainable solution for decentralized wastewater treatment in resource-limited communities.

Keywords: Adsorption, Domestic wastewater, Langmuir and Frendlich models, Laterite blocks, Kinetic models, Nitrate, Sulphate

1 Introduction

Nutrient pollution of domestic wastewater by nitrate (NO_3^-) and sulphate (SO_4^{2-}) has become a serious environmental issue, especially in areas that are quickly urbanizing and lack a centralized wastewater treatment infrastructure. While high sulphate concentrations in groundwater cause scaling, corrosion, and possible gastrointestinal health problems, excessive nitrate is linked to eutrophication methemoglobinemia (also known as "blue baby syndrome"), and long-term ecological damage [1]. Decentralized treatment methods are being researched in developing nations to reduce nutrient contamination and protect water supplies [2]. Because of its ease of use, low energy needs, and low sludge generation, adsorption has drawn a lot of interest as a cost-effective and efficient nutrient

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removal technique [3]. For rural and peri-urban population, adsorption-based systems utilizing natural materials provide sustainable alternatives to sophisticated physicochemical treatment methods. Numerous inexpensive adsorbents have shown encouraging nutrient removal properties, including biochar, natural clays, red mud, zeolites, and lateritic soils [4]. In places like Karnataka, India, laterite, a tropical residual soil high in iron and aluminium oxides, is widely accessible. It is a viable option for adsorption-based water treatment due to its high porosity, surface charge properties, and mineral makeup [5]. Laterite's iron and aluminium hydroxides improve surface complexation and anion exchange processes, which makes it easier to extract nitrate ion. Laterite-based materials have shown encouraging nitrate removal ability in recent investigations. For example, in ideal acidic circumstances (pH 3), a laterite–limestone mixture (60:40) increased removal effectiveness up to 72.32%, but raw laterite only managed a maximum nitrate removal efficiency of 56.32%. As per the Langmuir isotherm model, laterite's better adsorption was 0.628 mg/g, showing monolayer adsorption behaviour. Ettringite precipitation methods have been shown to have high sulphate removal efficiency. Using calcium sulfoaluminate as an aluminium source, this paper showed that sulphate removal efficiency of up to 98% were attained in domestic wastewater and 87% in industrial wastewater. These findings highlight the effectiveness of precipitation-based approaches for high-strength sulphate-laden effluents, particularly under alkaline conditions (pH 12–12.5) [6].

However, the efficiency of nitrate removal is often reduced by the presence of competing anions in wastewater, highlighting the significant influence of water matrix effects under real environmental conditions [7]. Adsorption isotherms are commonly used to describe the equilibrium relationship between the amount of adsorbate retained on the adsorbent surface and its equilibrium concentration in the aqueous phase at a constant temperature. These models provide valuable insight into the adsorption mechanism and the interaction between the adsorbent and adsorbate [8].

Previous studies using actual wastewater reported a nitrate removal efficiency of only 4.6% at an initial nitrate-nitrogen concentration of 1.3 mg/L, demonstrating the challenges associated with treating complex wastewater matrices [9]. Equilibrium adsorption behaviour has generally been evaluated using the Langmuir and Freundlich isotherm models. Although adsorption data may not perfectly conform to either model, the Langmuir isotherm frequently provides a better fit, suggesting that adsorption predominantly occurs as monolayer adsorption on relatively homogeneous active sites [10]. Contact time is another critical parameter affecting adsorption performance and the practical applicability of adsorption systems. It influences both the adsorption rate and the time required to achieve equilibrium. Previous studies investigated contact times ranging from 25 to 175 min while maintaining all other operating conditions constant [11]. The amount of adsorbate removed at each interval was determined to evaluate the adsorption kinetics and equilibrium behaviour.

Laterite-based materials have also shown considerable potential for nitrate removal from wastewater. Batch adsorption studies demonstrated that mixtures of laterite soil and laterite limestone effectively adsorb nitrate, with the highest removal efficiency achieved at pH 3. Adsorption equilibrium was reached after approximately 60 min for RL and 180 min for LD60, with a maximum nitrate adsorption capacity of 0.628 mg g^{-1} reported for laterite soil. The adsorption kinetics were successfully described using both pseudo-first-order and pseudo-second-order kinetic models, indicating that adsorption rate analysis is essential for understanding the governing removal mechanism [9].

The Langmuir and Freundlich isotherm models are the most widely used to describe adsorption equilibrium [10]. The Freundlich model assumes multilayer adsorption on heterogeneous surfaces, whereas the Langmuir model describes monolayer adsorption on homogeneous surfaces. Adsorption kinetics were further evaluated using pseudo-first-order and pseudo-second-order models to determine the rate-controlling mechanism [12]. Furthermore, scanning electron microscopy (SEM) revealed substantial changes in surface morphology after adsorption. The partial filling of pores and deposition of adsorbate species on the laterite surface confirmed the effective interaction between the adsorbent and wastewater constituents. The present study investigates the feasibility of laterite block filtration as a sustainable, low-cost, and locally available treatment technology for domestic wastewater remediation. Batch adsorption experiments were conducted using household wastewater to evaluate nitrate and sulphate removal efficiencies.

2 Materials and Methods

The two main supplies utilized during the experiment are household wastewater and laterite blocks. Laterite blocks were selected because of its high porosity, significant iron and aluminium oxide content, and inherent adsorption capacity, as an affordable alternative to conventional filter medium. To determine the effectiveness of laterite blocks in eliminating common domestic effluent contaminants such as suspended particles, nutrients, organic debris, and dissolved salts are among the several components found in domestic wastewater. Wastewater is produced in homes and communities by routine tasks like showering, laundry, and dishwashing. To make sure the sample fairly represents the pollution levels found in typical homes, natural wastewater was gathered from a drainage canal. Because it contains a range of pollutants, this effluent is ideal for testing the efficacy of laterite-based filtration.

2.1 *Collection of laterite blocks*

The laterite that was gathered from the Sakaleshpura had large concentrations of iron and aluminium oxides, which are typical of heavily worn tropical soils. Through processes including ion exchange and surface complexation, promotes nutrient adsorption on reactive surface sites by minerals contribution. In batch scale studies, enough surface contact with the wastewater is guaranteed by the moderate porosity and particle size dispersion. The combination of physical and chemical analysis confirms Sakaleshpura laterite's efficacy as a low-cost adsorbent medium in order to eliminate nitrate (NO_3^-) and sulphate (SO_4^{2-}) from household wastewater.

2.2 *Wastewater sample collection*

The open drainage canal in Hassan City, Karnataka, India, which carries mostly residential sewage mixed with little contributions from business facilities, provided the domestic wastewater utilized in this study. Using a GPS-enabled mobile device, the position of the sampling is around 12.9936° N latitude and 76.0858° E longitude. The drainage channel is an example of a typical urban residential wastewater stream in a metropolis that is expanding quickly, where direct discharge into surface drains and partial sewer connection are normal. The wastewater was a mixture of domestic wastewater from kitchens, bathrooms, and laundry sources, and it had a greyish colour with visible suspended particles, organic debris, and floating objects. The location was chosen to guarantee that the wastewater collected represented actual field conditions found in situations involving decentralized wastewater management. Samples were taken in sterile, high-density polyethylene (HDPE) containers under normal flow conditions during the day. To reduce variations in physicochemical properties, samples were brought to the lab in insulated cartons and examined within a day. Prior to experimental use, coarse debris was removed by sieving through a 1-mm mesh to avoid clogging during column and batch studies. Using established methods for wastewater and water analysis, the collected effluent was examined for nitrate (NO_3^-), sulphate (SO_4^{2-}), and other indicators. The wastewater's viability for examining nutrient transport and attenuation through laterite blocks medium was confirmed by the presence of significant nitrate and sulphate concentrations.

2.3 *Instruments used for nitrate and sulphate analysis*

Figure 1 shows UV-visible spectrophotometer (model DR 3900) made by Hach that is commonly used for physicochemical examination of wastewater and samples of water. The Beer-Lambert law governs how the gadget operates, which states that the analyst concentration and the absorbance of light flowing through a coloured solution is directly correlated. It covers an approximate wavelength range of 320–1100 nm using two light sources, usually a tungsten lamp for the visible area and a deuterium lamp for the UV.

Figure 1: UV –Spectrophotometer for wastewater analysis.

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Certain wavelengths are isolated by a monochromatic diffraction grating, and the transmitted light intensity is measured using a silicon photodiode detector. Both single-wavelength absorbance measurements and spectrum scanning for method development and verification are made possible by this setup. When TNT plus vials is inserted, in-built barcode recognition immediately recognizes preprogramed test procedures, and a closed optical chamber minimizes interference from ambient light. For typical water quality metrics including nitrate, nitrite, ammonia, phosphate, sulphate, iron, manganese, demand for chemical oxygen (COD), and other general water quality indicators, the instrument has a large library of factory-calibrated procedures. By eliminating the requirement for manual curve development, these integrated calibrations enable immediate reading of concentrations in standard units (such as mg/L), increasing repeatability and lowering analytical error. Operationally, the analysis entails preparing the sample (filter, digestion, or dilution as needed), adding certain reagents to produce a detectable colour, incubating for the required reaction time, and measuring absorbance at a chosen wavelength. The touchscreen interface retains commonly used programs, offers step-by-step procedural assistance, and carries out automated computations, such as statistical summaries and dilution correction. The results can be exported via USB for additional processing and documentation, or they can be saved internally. In order to ensure data dependability for research and compliance testing, the instrument also has quality assurance functions including automated wavelength checks, lamp performance monitoring, and blank correction.

The DR 3900's accuracy, user-friendliness, and broad range of parameters make it ideal for environmental engineering applications, especially characterization of domestic wastewater, monitoring of nutrient and sulphate concentrations, and assessment of the effectiveness of pollutant removal in adsorption studies employing inexpensive materials. All things considered, the spectrophotometer offers a strong and trustworthy analytical platform for routine environmental monitoring and laboratory-scale wastewater treatment research.

2.4 *Adsorption*

A substance's interaction with a solid or liquid phase is described by two essentially distinct mass transfer phenomena: adsorption and absorption. A surface phenomenon, known as adsorption, occurs when molecules of a material (adsorbate) gathered outside of a liquid or solid (adsorbent). Van der Waals forces are examples of physical forces or chemical connections between the adsorbate and the adsorbent's surface cause the process to take place. Pore structure, surface area, and surface functional groups, and pH, temperature, and contact time are examples of operational parameters. All significantly affect adsorption efficacy because of its surface-dependent nature. The physicochemical compatibility of the adsorbate and the adsorbing substrate and due to its high effectiveness, easy usage, and adsorbent regenerability, adsorption is frequently chosen for applications including water and wastewater treatment from an environmental engineering standpoint. It works well to remove dissolved pollutants such organic pollutants, heavy metals, nitrates, and sulphates.

2.5 *Adsorption isotherms*

The allocation of molecules adsorbed in the solid phase and the liquid surface at equilibrium and constant temperature is described by adsorption isotherms. They are necessary to comprehend the surface characteristics, adsorption capability and the ways in which the adsorbent (laterite) interacts with the adsorbate (such as metal ions or nitrate ions). The relationship is often symbolized by the quantity absorbable per adsorbent mass (q_e, mg/g) and the adsorbate's concentration in solution at equilibrium (C_e, mg/L). The relationship between the laterite surface and the contaminant is clarified by adsorption analysis isotherm. By using Freundlich and Langmuir models to match experimental data, it is crucial to determine whether adsorption occurs via monolayer surface binding or multilayer building laterite-based treatment systems by adsorption on diverse locations.

2.6 *Adsorption kinetics*

Adsorption kinetic modelling is an essential tool for elucidating the rate-controlling mechanisms involved in adsorption processes, including surface reactions, film diffusion, and intraparticle diffusion. Kinetic models provide insight into the adsorption mechanism by describing the relationship between the adsorption rate and the availability of active sites on the adsorbent surface. The pseudo-first-order model generally assumes that the adsorption rate is proportional to the

number of unoccupied adsorption sites and is commonly associated with physical adsorption. In contrast, the pseudo-second-order model assumes that chemisorption is the dominant mechanism, involving electron sharing or electron exchange between the adsorbent and adsorbate. This model has been widely applied to the adsorption of metal ions, nitrate, sulphate, and other inorganic contaminants onto iron oxide-rich lateritic materials. In addition to pseudo-first-order and pseudo-second-order models, the intraparticle diffusion model is commonly employed to evaluate whether diffusion within the pores of the adsorbent contributes to the overall adsorption rate. Furthermore, the Elovich model is frequently used to describe chemisorption on energetically heterogeneous surfaces, providing additional evidence of the heterogeneous nature of laterite. Collectively, these kinetic models demonstrate that contaminant removal by laterite is governed by a combination of surface chemical interactions and diffusion-controlled mechanisms rather than by a single adsorption process.

2.7 *Batch adsorption experimental setup*

To evaluate the filtration performance of laterite block media for the treatment of domestic wastewater, a laboratory-scale continuous-flow filtration system was constructed using two storage tanks. Laterite blocks were arranged within a rectangular filtration channel to form the filter medium, allowing domestic wastewater to flow through the system under controlled hydraulic conditions [13]. All laterite blocks had identical dimensions of 1.0 ft × 0.8 ft × 0.8 ft. The filtration channel measured 6.5 ft in length, 1.7 ft in width, and 1.0 ft in depth. A digital flow meter was installed at the inlet of the filtration system to accurately monitor and regulate the hydraulic conditions throughout the experiments. Flow rates of 1.0, 1.5, and 2.0 L min^{-1} were established using a control valve and verified by the digital flow meter. This arrangement minimized experimental errors, ensured precise flow regulation, and provided consistent hydraulic loading during the filtration experiments.

3 Results and Discussion

3.1 *Assessment of nitrate and sulphate in domestic wastewater*

Table 1 shows the starting levels of the target contaminants, sulphate and nitrate, in the raw household wastewater that was gathered for this investigation. 23 mg/L of sulphate and 13.2 mg/L of nitrate were found in the influent wastewater, suggesting the presence of dissolved inorganic nutrients frequently seen in household sewage. The adsorption performance of the laterite adsorbent under batch and continuous-flow settings was assessed and used these baseline concentrations as the starting contaminant levels [14][15].

Table 1: Concentrations of nitrate and sulphate in the influent domestic wastewater.

Parameter	Concentration
Sulphate (mg/L)	23
Nitrate (mg/L)	13.2

3.2 *Adsorption isotherms*

A graph of C_e on the X-axis and C_e/Q_e on the y-axis was plotted, where C_e represented the adsorbate's equilibrium concentration in solution following adsorption and Q_e represented the quantity of adsorbed adsorbate per unit of mass of adsorbent. A graph of $Logc_e$ on the x-axis and $LogQ_e$ on the y-axis was plotted in the Freundlich model. To get the regression value R^2 trend lines were created on both models. The R^2 values for the Langmuir model were closer to 1, indicating a superior fit compared to the Freundlich model. The laterite's chemical and physical properties drastically influence the adsorption behaviour of laterite towards organic and inorganic pollutant. The adsorption kinetics and mechanism involving chemical binding as well as mass transport are affected greatly by physical and chemical properties of the laterite [16]. The process of adsorption on applicability of heterogeneous surface energy is used to evaluate the Freundlich model [17].

3.2.1 Nitrates adsorption isotherm models

The Langmuir isotherm (Table 2) model exhibited an excellent correlation with the experimental data (R^2 = 0.98588), indicating a better fit than the Freundlich model (Figure 2). The linearized Langmuir isotherm suggests that nitrate adsorption predominantly occurred through monolayer coverage on relatively homogeneous adsorption sites. However, the linear regression produced a negative intercept, resulting in

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a non-physical Langmuir constant. This indicates a slight deviation from the ideal assumptions of the Langmuir model.

The occurrence of a negative intercept may be attributed to several factors, including surface heterogeneity, pore diffusion effects, experimental uncertainties, or partial multilayer adsorption, which are commonly observed in natural adsorbents such as laterite. Consequently, although the Langmuir model provides an excellent statistical fit to the experimental data, the adsorption system does not fully satisfy all of the theoretical assumptions underlying the Langmuir isotherm. These findings suggest that the adsorption process is predominantly monolayer in nature but may also be influenced by the inherent structural heterogeneity and complex surface characteristics of laterite.

Table 2: Nitrate–Isotherm values.

C_e/Qe (l/g)	LogCe (mg/l)	$LogQ_e$ (mg/g)
0.575471698	0.785329835	1.02530587
0.704081633	0.838849091	0.99122608
0.776595745	0.86332286	0.97312785
0.192857143	0.431363764	1.14612804
0.427350427	0.698970004	1.06818586
0.815217391	0.875061263	0.96378783

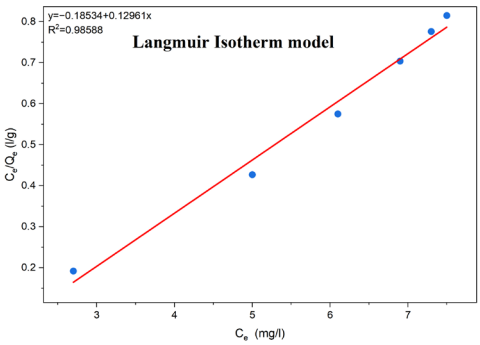

Figure 2: Nitrate-Langmuir adsorption isotherm.

Figure 3 shows Freundlich isotherm model has a correlation value (R^2 = 0.96266) (Table 3), suggesting that as it is common for naturally occurring porous geomaterials. This high R^2 value implies that nitrate adsorption onto the laterite medium takes place heterogeneous surface with an uneven adsorption distribution energy. The intercept, log K_f = 1.3307, yields $K_f \approx 21.4$ (mg g^{-1}) (L $mg^{-1})^{1/n}$, which represents the adsorbents total adsorption capacity. Iron and aluminium oxides provide active sorption sites; this number suggests that the laterite material has a moderate affinity for nitrate ions.

The Langmuir and Freundlich equations were employed to clarify the properties of nitrate adsorption. The connection between C_e (in the X-axis) and C_e/Q (in the Y-axis) can be seen in the graph plotted using the Langmuir equation, but the connection between logC_e (in the X-axis) and logQ_e (in the Y-axis) can be seen in the graph according to the Fruendlich equation. Both Freundlich and Langmuir isotherm models were used to evaluate the equilibrium adsorption data, Langmuir had a greater correlation coefficient (R^2 = 0.98588) compared to the Freundlich model (R^2 = 0.96266), indicating that a more realistic depiction of the Langmuir isotherm adsorption process. This implies that adsorption mostly takes place as a monolayer on a surface that is comparatively homogenous and has a limited number of active sites. Nonetheless, the Freundlich model's rather excellent match also suggests some surface heterogeneity, which is common for natural adsorbents. As a result, even if monolayer adsorption predominates, surface imperfections may cause slight departures from optimal Langmuir behaviour. Langmuir isotherm is the best model to illustrate the adsorption mechanism according to the isotherm studies[18]. The evaluation process involves many parameters for the performance of fixed bed column such as initial concentration solution, flow rate, amount of adsorbent used and particle size of the adsorbent. The increased adsorbent dose in column enhances the adsorbent capacity of the bed [19].

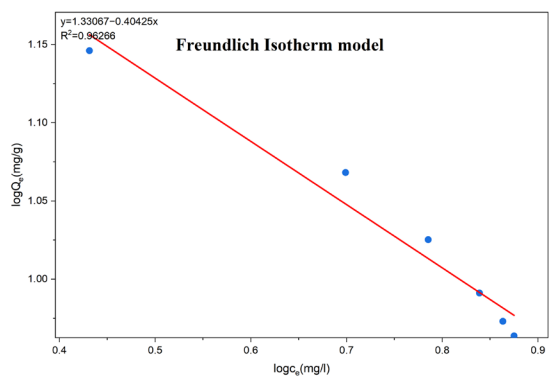

Figure 3: Nitrate-Freundlich adsorption isotherm.

Table 3: Nitrate- Isotherm regression values.

Model	R^2
Langmuir	0.98588
Freundlich	0.96266

3.2.2 *The results of sulphates adsorption isotherm*

The Langmuir model exhibited an excellent correlation with the experimental data ($R^2 = 0.99302$), demonstrating its superior ability to describe the equilibrium adsorption behaviour of sulphate onto laterite. The sulphate adsorption (Table 4) was better described by the Langmuir isotherm model (Figure 4) than by the Freundlich model, indicating that the adsorption process predominantly occurred through monolayer adsorption on relatively homogeneous adsorption site. This finding is consistent with previous studies, which reported that the Langmuir isotherm provides a better representation of adsorption systems exhibiting monolayer coverage and finite adsorption sites [17]. Although both the Langmuir and Freundlich models are widely used to describe equilibrium adsorption behaviour, the higher correlation coefficient obtained for the Langmuir model suggests that monolayer adsorption was the dominant mechanism in the present study. The excellent agreement between the experimental and predicted adsorption data further confirms the suitability of the Langmuir model for describing sulphate adsorption by laterite. These results demonstrate that laterite is an effective, low-cost adsorbent for sulphate removal from domestic wastewater owing to its high adsorption capacity and strong affinity for sulphate ions. Consequently, laterite-based filtration systems show considerable potential as sustainable and environmentally friendly technologies for decentralized domestic wastewater treatment.

Figure 5 shows the isotherm of Freundlich which provides a better description of sulphate adsorption onto laterite, suggesting that non-uniform adsorption energies and heterogeneous surface interactions control the process. A considerable adsorption potential is shown by the comparatively high K_f value, especially at lower sulphate concentrations. Nonetheless, a negative intercept in the linear Freundlich plot or a negative adsorption intensity parameter ($1/n < 0$) indicates optimal adsorption behaviour. Since adsorption capacity is represented by log K_f, the intercept in the Freundlich equation corresponds to log K_f, which should theoretically be positive. Uncertainties in the experiment, a narrow concentration range, or decreased adsorption effectiveness at higher sulphate concentrations can all result in a negative intercept. It may also mean that adsorption sites quickly reach saturation or that incoming ions and already-adsorbed sulphate ions interact repulsively.

Table 4: Sulphate-Isotherm values.

C_e/Q_e (l/g)	$LogC_e$ (mg/l)	$LogQ_e$ (mg/g)
0.513513514	1.278753601	1.56820172
0.302325581	1.113943352	1.63346846
0.142857143	0.84509804	1.69019608
0.12	0.77815125	1.69897
0.217391304	1	1.66275783
0.166666667	0.903089987	1.68124124

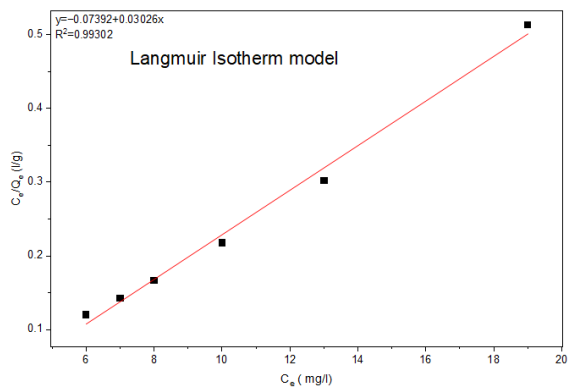

Figure 4: Sulphate-Langmuir adsorption isotherm.

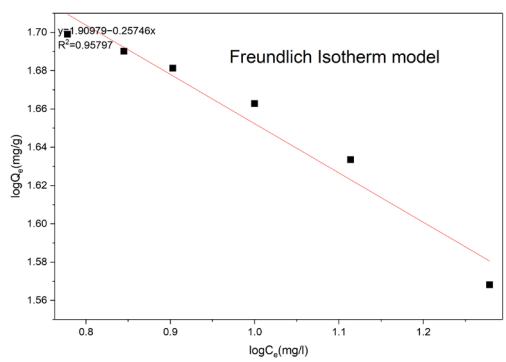

Figure 5: Sulphate-Freundlich adsorption isotherm model.

Table 5: Sulphate- Isotherm regression values.

Model	R^2
Langmuir	0.99302
Freundlich	0.95797

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The Freundlich and Langmuir isotherm models were used to examine the equilibrium adsorption data, and Table 5 displays the associated coefficients of determination (R^2). A better match to the results of the experiment were shown by the isotherm of Langmuir, which had a higher R^2 value (0.99302) compared to the Freundlich isotherm (0.95797). Most of the adsorption process occurs as monolayer coverage on a homogenous adsorbent surface, physical adsorption on structured surfaces, this suggests consistent adsorption energies and minimal interaction between adsorbed species. The Freundlich model also showed a good match, but its relatively low R^2 value suggests that multilayer adsorption and surface heterogeneity are less important within the existing system. The adsorption behaviour is more consistent with Langmuir assumptions than heterogeneous surface interactions, as further shown by the Freundlich model. Overall, the Langmuir isotherm's greater regression coefficient validates the adsorbent's aptitude for effective contaminant removal under equilibrium circumstances by confirming that the process of adsorption is surface-limited and monolayer-controlled.

3.3.3 Nitrates- adsorption kinetic models

Figure 6 demonstrates the pseudo-first-order kinetic model, which was employed to investigate the nitrate dynamics of adsorption. The adsorption process primarily follows first-order kinetics, as seen by the relatively excellent correlation (R^2 = 0.90562) in the linear plot of ln ($Q_e - Q_t$) vs. time. A modest adsorption rate is suggested by the rate constant (k_1), which was found to be 0.01058 min^{-1}. As stated by the model, nitrate removal is mostly controlled by physical adsorption onto accessible surface sites, with quick absorption in the early phases and a slow approach to equilibrium as active sites are saturated.

Figure 7 shows highly high coefficient of determination (R^2 = 0.99749), which indicates that the pseudo-second-order kinetic model suited the experimental adsorption data well. The linearized pseudo-second-order equation (t/Q_t vs. t) accounts for around 99.75% of the variability during the adsorption data, according to an R^2 value of near unity. The process of adsorption closely resembles pseudo-second-order kinetics, with little variation across the whole time span, the linear regression equation (Y = 0.47429 + 0.98178X) further illustrates the consistency of the experimental and model-predicted values. The almost perfect linearity indicates that Valence forces are involved in chemisorption by exchange or sharing of electrons between the adsorbate (sulphate ions) and the active sites that are currently functioning on the laterite surface, is probably the rate-controlling mechanism.

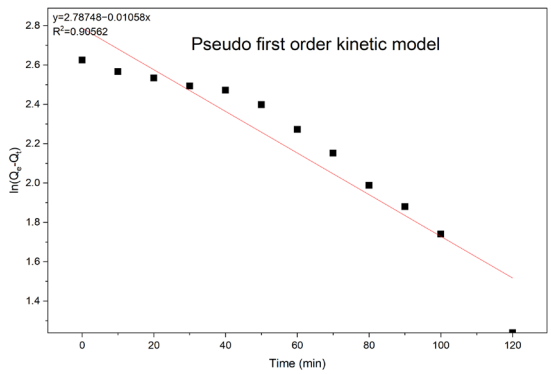

Figure 6: Nitrate-Model of pseudo-first order kinetics.

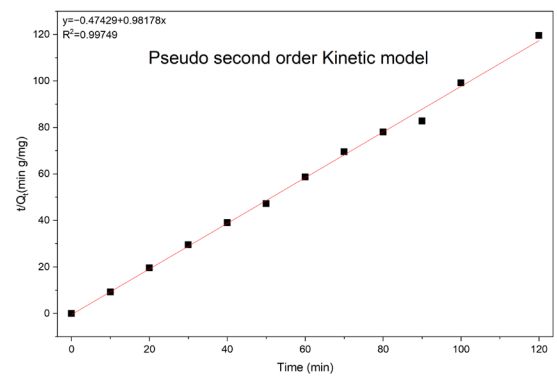

Figure 7: Nitrate-model of pseudo-second-order kinetics.

3.3.4 Sulphates- adsorption kinetic models

The excellent linear connection indicated by the high R^2 value (0.9223) verifies the outstanding dependability of pseudo-first-order kinetics in sulphate adsorption. The pseudo-first-order kinetic model was utilized to analyse the sulphate dynamics of adsorption. Figure 8 shows pseudo-first-order kinetic model, according to the linear plot of ln ($Q_e - Q_t$) vs time, which showed a good correlation value (R^2 = 0.9223). A comparatively fast adsorption rate was indicated by the pseudo-first order rate constant (k_1), which was discovered to be 0.01747 min^{-1}. The model yielded an equilibrium adsorption

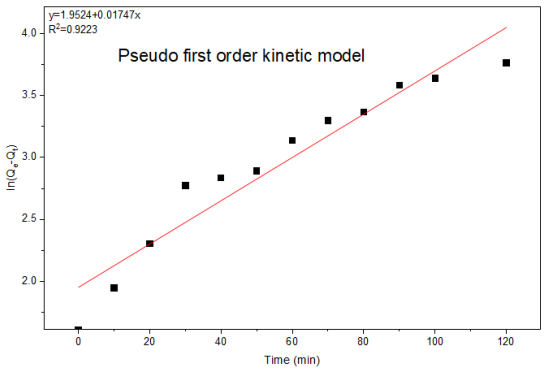

Figure 8: Sulphate-model of pseudo-first-order kinetics**.**

capacity (Q_e) of 7.04 mg/g. The findings imply that physical adsorption processes dominate the removal of sulphate, and that the availability of surface adsorption sites regulates the pace of absorption.

Figure 9 indicates the pseudo-second-order kinetic model plot which demonstrates a strong linear connection between t/Q_t and time (t) with high R^2 = 0.97949. An excellent match between the results of the experiment and the pseudo second order kinetic model is shown by an R^2 value of near 1. In particular, the model explained the variance during the adsorption data, showing that the process of adsorption adheres to second order reaction kinetics [20] . The study strongly evidences the Sulphate removal by chemisorption adsorption from the laterite soil. Chemisorption, which involves valence forces by sharing electrons or exchange among the adsorbent surface, controls the rate-limiting process.

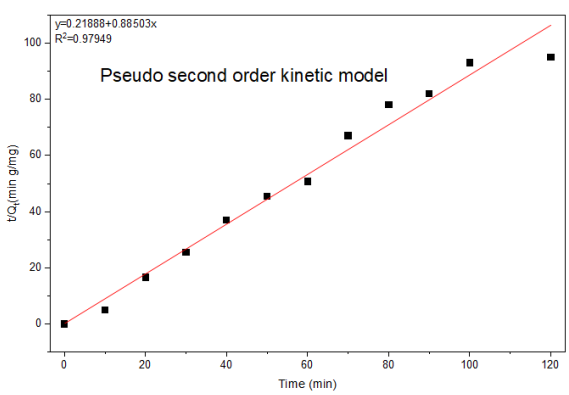

Figure 9: Sulphate-model of pseudo-second-order kinetics.

3.4 *Mechanistic studies for adsorption*

Figure 10 presents the SEM micrograph of the laterite surface before adsorption. The surface exhibits a highly porous, rough, and irregular morphology with numerous voids and interconnected pore channels. The particles appear angular and loosely aggregated, providing a high specific surface area and abundant active adsorption sites. The presence of surface cavities and micropores facilitates the diffusion and mass transfer of adsorbate ions into the internal pore structure of the material. These structural characteristics contribute to the excellent adsorption performance of laterite and support its suitability as an effective adsorbent for wastewater treatment.

Figure 11 illustrates the SEM micrograph of the laterite surface after adsorption. Significant morphological changes are observed following the adsorption process [21][22]. The surface becomes denser and smoother, while many of the pores and cavities are partially or completely filled with adsorbed species. The reduction in pore size and porosity indicates that adsorbate ions were successfully deposited onto the active sites and within the internal pore structure of the laterite. These observations suggest that adsorption occurred on both the external surface and within the internal pores of the adsorbent. The SEM analysis provides direct visual evidence of the adsorption process through pore filling and surface deposition of adsorbate species. These findings confirm the effectiveness of laterite as an adsorptive filtration medium and support the proposed adsorption mechanism responsible for the removal of contaminants from domestic wastewater[23].

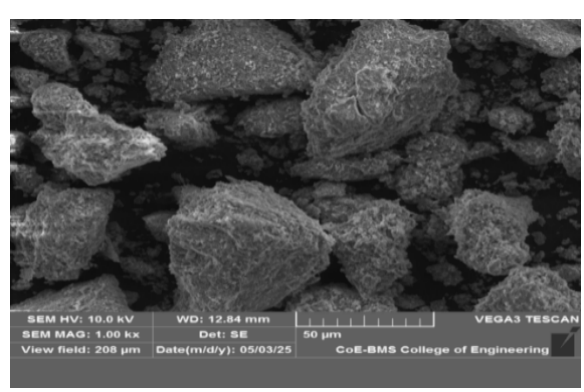

Figure 10: SEM image of raw laterite sample.

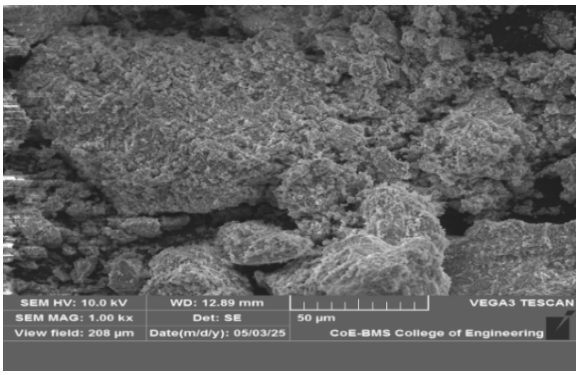

Figure 11: SEM image of laterite after adsorption.

4 Conclusions

The present study comprehensively evaluated the potential of laterite blocks as a cost-effective, sustainable, and locally available adsorbent for the removal of nitrate (NO_3^-) and sulphate (SO_4^{2-}) from domestic wastewater. Batch adsorption experiments demonstrated that laterite exhibited high removal efficiency for both contaminants. Equilibrium analysis showed that the Langmuir isotherm model provided a better fit to the experimental data for both nitrate (R^2 = 0.98588) and sulphate (R^2 = 0.99302) than the Freundlich model, indicating that adsorption predominantly occurred through monolayer coverage on relatively homogeneous adsorption sites. Although the Freundlich model also exhibited strong correlations for nitrate (R^2 = 0.96266) and sulphate (R^2 = 0.95797), its comparatively lower correlation coefficients suggest that surface heterogeneity played a secondary role within the concentration range investigated.

Adsorption kinetics were better described by the pseudo-second-order model than by the pseudo-first-order model, indicating that chemisorption involving valence forces and surface interactions was the dominant rate-controlling mechanism. The rapid initial adsorption followed by a slower approach to equilibrium further suggests that adsorption was initially governed by the availability of active surface sites and subsequently influenced by intraparticle diffusion. SEM analysis revealed significant pore filling and surface coverage after adsorption, providing morphological evidence that supports the proposed adsorption mechanism.

Despite these promising findings, several limitations should be acknowledged. First, the batch adsorption experiments were conducted under controlled laboratory conditions, which may not fully represent the complex hydraulic and chemical conditions encountered in practical domestic wastewater treatment systems. Second, the regeneration and reusability of the laterite blocks were not investigated, limiting the assessment of their long-term operational performance and economic feasibility.

Future research should therefore focus on continuous-flow and pilot-scale studies under realistic operating conditions to validate the applicability of laterite-based filtration systems for decentralized wastewater treatment. In addition, investigations into the regeneration, reuse, and long-term stability of laterite adsorbents are essential for evaluating their practical feasibility, sustainability, and cost-effectiveness in real-world applications.

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Author Contributions

Amrutha D S: Conceptualization, data curation, methodology, investigation and writing the original draft.; Kiran B M: Supervision and report editing.

Conflicts of Interest

The authors declare no conflict of interest. Authors have agreed to publish the version of the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the Grammarly tool to enhance the language and readability of the manuscript.

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