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Investigation of TiO_2-Impregnated Laterite (TIL) as an Adsorbent for Arsenic Removal in Aqueous Media

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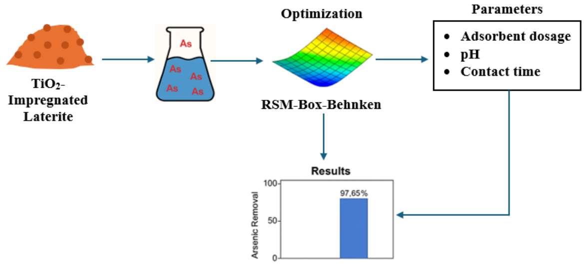
Graphical abstract



Abstract

Arsenic contamination in groundwater poses a critical threat to public health, particularly in developing regions. This study investigates the potential of TiO_2-impregnated laterite (TIL) as a cost-effective and sustainable adsorbent for arsenic removal from aqueous solutions. A Box–Behnken design within the framework of Response Surface Methodology (RSM) was employed to optimize three key operational parameters: adsorbent dosage, solution pH, and contact time. The TiO_2-laterite composite was synthesized through impregnation, aging, and calcination processes to enhance adsorption capacity. Experimental results indicated that adsorbent dosage and reaction time had significant effects on arsenic removal efficiency, whereas pH had a minor influence within the tested range. Under optimized conditions (0.99 g dosage, pH 5.3, 71 minutes), the process achieved 97.65% arsenic removal, closely matching the model-predicted 98.82% with $R^2 = 0.996$. These results demonstrate strong model reliability and high performance of the TiO_2-laterite composite. The findings demonstrate that TiO_2-impregnated laterite is a promising material for arsenic remediation, offering high performance, economic feasibility, and scalability. However, further research is needed to validate performance under field conditions, analysis material characterization, assess long-term stability, and explore regeneration capacity.

Keywords: TiO_2-Impregnated Laterite, adsorption, arsenic removal, water treatment, process optimization.

1. Introduction

Arsenic contamination in groundwater poses a critical threat to environmental sustainability and public health, particularly in South and Southeast Asia, where millions of people rely on arsenic-laden aquifers for drinking water and daily use (Shaji *et al.* 2021). Recognized as a Group I carcinogen by the World Health Organization (WHO 2019), chronic exposure to arsenic—even at low concentrations—has been associated with a range of severe health conditions including skin lesions, cardiovascular diseases, developmental impairments, and various cancers (Aredes and Pawlik 2013; Jadhav *et al.* 2015). Arsenic typically exists in water in inorganic forms as arsenite [As(III)] and arsenate [As(V)], with the former being more mobile and toxic (Smedley and Kinniburgh 2001). The complex geochemical behavior of arsenic in subsurface environments, coupled with limited infrastructure in many affected regions, makes its remediation particularly challenging (Carrard *et al.* 2019; McCarty *et al.* 2011).

A range of physicochemical technologies has been developed for arsenic removal, including ion exchange, membrane filtration, electrocoagulation, and adsorption (Alkurdi *et al.* 2019; Mollah *et al.* 2001). Among these, adsorption has emerged as a promising approach due to its operational simplicity, low cost, and scalability, especially in decentralized or resource-limited settings (Simonič 2009). Naturally occurring materials such as laterite—a weathered soil rich in iron and aluminum oxides—have shown significant potential as cost-effective adsorbents for contaminant removal from water (Iriel *et al.* 2017). However, the adsorption capacity of unmodified laterite is often limited, prompting research into surface modification strategies to enhance its performance.

The utilization of modified laterite in wastewater treatment has garnered increasing attention due to its potential as an effective and sustainable adsorbent material. Vu *et al.* (2020) demonstrated that nanocomposite materials based on polyanion-modified laterite, specifically with polystyrene sulfonate (PSS), exhibit high performance in removing antibiotics such as tetracycline from wastewater. This indicates that chemical modification of laterite can enhance its adsorption capabilities for specific contaminants, making it a promising candidate for targeted pollutant removal (Vu *et

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al. 2020). Further research by Nidheesh *et al.* (2021) explored the application of alkali-modified laterite soil as a heterogeneous catalyst in combined electro-Fenton and electrocoagulation processes for industrial wastewater treatment. The study found that modification of laterite improved the efficiency of pollutant degradation, highlighting the importance of surface modifications in enhancing the reactivity and treatment performance of laterite-based materials (P.V *et al.* 2021). Similarly, Changduang *et al.* (2021) developed reactive iron-coated natural filter media, which included modifications to natural materials like laterite, to effectively treat antibiotic residuals in swine wastewater, emphasizing the role of surface coatings in improving contaminant removal mechanisms (Changduang *et al.* 2021). Besides, Tuan *et al.* (2025) research team also conducted experiments and investigated the ability to treat Arsenic in wastewater by adsorption of laterite modified with $KMnO_4$. The results confirmed that $KMnO_4$-modified laterite is a promising material for arsenic remediation, offering a sustainable and scalable solution (Tuan *et al.* 2025). In addition to chemical modifications, physical and structural enhancements of laterite have been investigated. For instance, Zhao *et al.* (2020) discussed the broader application of various flocculants, including modified polymeric flocculants, in oily wastewater treatment, suggesting that modifications to natural materials like laterite could be integrated with such flocculants to improve coagulation and flocculation processes (Zhao *et al.* 2020). Although not specific to laterite, this indicates the potential for combining surface modifications with other treatment agents to optimize removal efficiencies. The environmental implications and scalability of modified laterite are also considered critical. Guo *et al.* (2023) provided a life-cycle assessment of wastewater treatment processes, including the use of modified materials, emphasizing the need to balance treatment efficacy with energy consumption and resource use (Guo *et al.* 2023). Surface engineering of nanostructured adsorbents, as discussed by Zhang *et al.* (2024), further underscores the importance of developing environmentally safe and scalable modified adsorbents, which could include modified laterite, for future wastewater treatment applications (Zhang *et al.* 2024). Overall, the body of research suggests that chemical and physical modifications of laterite significantly enhance its adsorption and catalytic properties, making it a versatile material for removing a wide range of contaminants from wastewater. These modifications not only improve treatment performance but also align with sustainability goals by utilizing natural and abundant resources, as highlighted across multiple studies.

Following the advancement, the recent studies have demonstrated that impregnating laterite with metal oxides or nanoparticles can significantly increase its surface area, active sites, and affinity for specific pollutants (Mostafa *et al.* 2025; Singh and Maiti 2024). In particular, titanium dioxide (TiO_2), a widely studied photocatalyst and adsorbent, has attracted attention due to its strong affinity for oxyanions, high stability, and environmental compatibility (Gatou *et al.* 2024). When immobilized on porous supports such as laterite, TiO_2 can enhance arsenic uptake via surface complexation and redox reactions, while potentially maintaining cost-effectiveness for large-scale deployment (Maiti *et al.* 2012). Also, TiO_2 offers dual advantages—surface activation and photocatalytic oxidation—which are absent in traditional modifiers like $KMnO_4$ or PSS. Its environmental safety and proven performance in oxyanion removal justify its selection.

This study aims to investigate the effectiveness of TiO_2-impregnated laterite (TIL) as an adsorbent for arsenic removal from aqueous solutions. A Box–Behnken design within the Response Surface Methodology (RSM) framework was employed to evaluate the effects of key operational parameters—including adsorbent dosage, solution pH, and contact time—on arsenic removal efficiency. The study further seeks to determine the optimal conditions for maximum removal and assess the viability of TIL as a low-cost, sustainable adsorbent for arsenic remediation in real-world applications.

2. Methodology

2.1. Preparation of Arsenic-contaminated wastewater

In this study, approximately 5 liters of synthetic arsenic-contaminated wastewater were prepared by diluting a 500 ppm arsenic AAS standard solution with deionized water to replicate polluted conditions under controlled laboratory settings. The initial arsenic concentration was set at 100 ppb, intentionally higher than typical concentrations found in natural groundwater, to provide a rigorous assessment of the removal efficiency. Prior to the adsorption experiments, the pH of each solution was measured and adjusted to the target values using sodium hydroxide (NaOH) to raise the pH or hydrochloric acid (HCl) to lower it. Once the desired pH was achieved, the adsorption process commenced, enabling the evaluation of arsenic removal performance under consistent and reproducible conditions within the defined experimental parameters.

2.2. Preparation of TiO_2-Impregnated Laterite

Nano titanium dioxide, purity 99.8%, particle size 5-10nm, was provided by Biotio Shanghai Corp Co., LTD. The size characteristics of Nano titanium dioxide are shown in **Figure 1**. To prepare the TiO_2-impregnated laterite (TIL) adsorbent, natural laterite was first collected, washed thoroughly with tap water followed by deionized water to remove dust and surface impurities, then oven-dried at 105°C for 24 hours. The dried material was crushed and sieved to obtain a uniform particle size of 4–5 mm. Take the ordinary laboratory beaker, add 200ml deionized water and 2.0g nano TiO_2 powder, and stir well. The nanometer titanium dioxide has the characteristics of easy precipitation, so it is necessary to add a certain amount of Sodium Lauryl Sulfate (K12) to the beaker, which can make nano titanium dioxide suspended in the beaker uniformly for 30 min. Then put the beaker in an ultrasonic oscillator, so that the nano carbon dioxide can be uniformly dispersed in the deionized water. The laterite particles were then immersed in the TiO_2 solution at a solid-to-liquid ratio of 1:10 (weight/volume) and stirred for 4 hours to ensure uniform impregnation. After impregnation, the material was aged at room temperature for 12 hours, followed by filtration and drying at 105°C for another 12 hours. Finally, the dried composite was calcined in a muffle furnace at 450°C for 3 hours to convert the precursor into crystalline TiO_2 and enhance the surface interaction between the laterite matrix and the titanium dioxide coating. The resulting TiO_2-impregnated laterite was stored in airtight containers for further characterization and use in adsorption experiments.

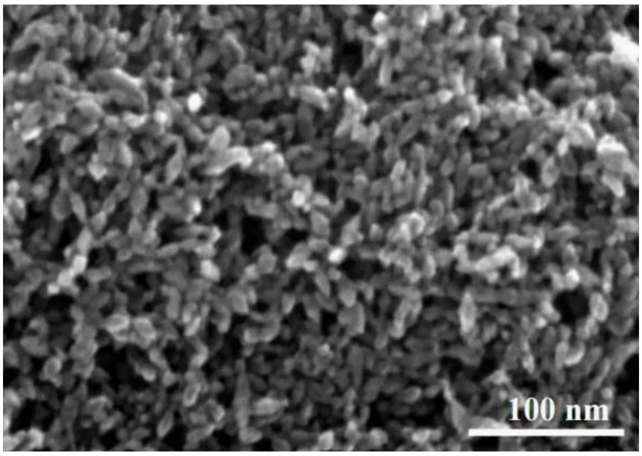

Figure 1. The size characteristics of Nano titanium dioxide[1]

2.3. Box–Behnken experimental design

The Box–Behnken design (BBD), a statistical approach within the broader framework of response surface methodology (RSM), is widely utilized to optimize processes and evaluate the influence of multiple variables and their interactions on a given response (Ferreira *et al.* 2007). In this research, BBD was applied to investigate how key operational parameters affect arsenic removal efficiency and to optimize the adsorption conditions accordingly. Unlike full factorial designs, BBD employs a three-level, incomplete factorial structure, enabling the modeling of nonlinear or quadratic effects with fewer experimental runs. This approach enhances efficiency by reducing the number of required tests, thereby saving time and resources while maintaining statistical robustness.

Design-Expert software (version 13) was used to construct the experimental matrix, analyze the results, and determine optimal process conditions for arsenic adsorption. The software facilitated the development of a predictive response surface model by fitting experimental data and estimating the coefficients associated with each factor. The independent variables assessed in this study were adsorbent dosage, solution pH, and reaction time. These parameters were varied within defined limits—dosage (0.01–1.0 g), pH (2–9), and reaction time (10–80 minutes)—based on prior experimental evidence to ensure relevance. Each factor was encoded at three levels: low (−1), center (0), and high (+1), allowing the exploration of curvature and complex interactions among variables.

In this study, the adsorption of arsenic from aqueous solutions was investigated using TiO_2-Impregnated Laterite to enhance the natural laterite adsorption capacity. Batch adsorption experiments were conducted by mixing known concentrations of arsenic-contaminated water with a fixed dose of the modified laterite under varying conditions of pH, contact time, adsorbent dosage, and initial arsenic concentration as designed by BBD. The mixtures were agitated at constant temperature, then filtered, and the residual arsenic concentration was collected in 200 mL amber bottles to prevent light-induced reactions, and the residual arsenic concentrations were measured using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). For accuracy, the initial arsenic concentrations of the synthetic wastewater were also analyzed using the same method, allowing for precise evaluation of removal performance.

The percent arsenic removal was calculated using **Equation 1.**

$$\%As\,removal = \left(\frac{A_0 - A_t}{A_o}\right) * 100\% \qquad (1)$$

In which: A_0: Initial arsenic concentration, A_t: Residual arsenic concentration

3. Results and Discussion

In this study, an initial arsenic concentration of 100 ppb was used in the preparation of synthetic contaminated wastewater to assess the efficiency of the adsorption process. This concentration was selected to reflect a moderate level of arsenic contamination, providing a suitable basis for evaluating removal performance and optimizing operational conditions. The outcomes of the experimental trials are detailed in the following section.

3.1. An empirical correlation between the arsenic removal efficiency and the three factors

Seventeen experimental runs were performed in total, with each run repeated three times to ensure statistical robustness. Furthermore, the experiment conducted under optimal conditions was also replicated three times to verify the consistency of the results. **Table 1** presents the detailed experimental parameters and corresponding arsenic removal efficiencies, all based on an initial arsenic concentration of 100 ppb. From the experimental implementation, the research team realized that the adsorbent material was not uniform between experiments (unlike the solution in the absorption). To avoid errors due to the heterogeneity of the adsorbent material, the research team repeated the experimental results at the center point in the BBD (run 13 to run 17). This helped to achieve uniformity of the adsorbent material between experiments. In a simple term, these center points are like "anchors" to keep the response surface from rotating around the central axis. To ensure reliability, each experiment was conducted in triplicate, with particular emphasis on repeating the center points to reduce variability associated with adsorbent

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[1] Provided by chemical vendor.

heterogeneity. The high R^2 value (0.996) confirms the statistical reliability of the model.

Table 1. Box-Behnken design experiment conditions, results of arsenic removal using TiO_2-Impregnated Laterite

RUN	Dosage (g)	pH	Reaction time (min)	Arsenic removal %
1	0.010	5.5	10	65.19
2	1.000	5.5	10	92.10
3	0.010	5.5	80	74.93
4	1.000	5.5	80	98.15
5	0.010	2.0	45	72.19
6	1.000	2.0	45	96.02
7	0.010	9.0	45	71.64
8	1.000	9.0	45	96.73
9	0.505	2.0	10	75.22
10	0.505	2.0	80	83.00
11	0.505	9.0	10	76.97
12	0.505	9.0	80	81.89
13	0.505	5.5	45	86.95
14	0.505	5.5	45	89.13
15	0.505	5.5	45	86.46
16	0.505	5.5	45	88.65
17	0.505	5.5	45	87.41

Table 2. ANOVA for percent arsenic removal using TiO_2-Impregnated Laterite.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	1498.74	9	166.53	178.38	< 0.0001	significant
A-Dosage	1137.84	1	1137.84	1218.81	< 0.0001	
B-pH	0.0009	1	0.0009	0.0009	0.9767	
C-Reaction_time	30.31	1	30.31	32.47	0.0007	
AB	0.3969	1	0.3969	0.4251	0.5352	
AC	3.40	1	3.40	3.65	0.0978	
BC	2.04	1	2.04	2.19	0.1824	
A^2	0.0671	1	0.0671	0.0719	0.7963	
B^2	50.08	1	50.08	53.64	0.0002	
C^2	105.32	1	105.32	112.81	< 0.0001	
Residual	6.53	7	0.9336			
Lack of Fit	1.41	3	0.4684	0.3653	0.7829	not significant

The experimental results outlined in **Table 1** demonstrate the influence of adsorbent dosage, pH, and reaction time on arsenic removal efficiency using TiO_2-impregnated laterite. Overall, higher dosages of the adsorbent were strongly associated with greater removal percentages. Specifically, when the dosage was increased from 0.01 g to 1.0 g, the removal efficiency rose significantly—for example, from 65.19% (Run 1) to 92.10% (Run 2) at a constant pH of 5.5 and reaction time of 10 minutes. Similarly, at 80 minutes of reaction time and the same pH, efficiency improved from 74.93% (Run 3) to 98.15% (Run 4). These trends confirm the critical role of adsorbent quantity in enhancing surface area and active sites for arsenic adsorption. Reaction time also had a positive effect, particularly at intermediate dosages (e.g., Run 9 vs. Run 10), indicating that longer contact times facilitate greater arsenic uptake until reaching near-equilibrium. The effect of pH appeared less pronounced, though mildly acidic to neutral conditions (pH 5.5) consistently yielded higher removal compared to strongly acidic (pH 2.0) or alkaline (pH 9.0) conditions. Notably, the central point replicates (Runs 13–17) showed consistent performance, with arsenic removal ranging from 86.46% to 89.13%, confirming the reproducibility and reliability of the experimental design. These findings underscore the importance of optimizing dosage and contact time, while indicating that TiO_2-impregnated laterite is an effective adsorbent across a moderate pH range.

The ANOVA results for percent arsenic removal presented in **Table 2** indicate that the quadratic model is highly significant, with a p-value of < 0.0001 and an F-value of 178.38, confirming the model's suitability for predicting arsenic removal efficiency. Among the independent variables, adsorbent dosage (A) was the most influential factor, exhibiting an exceptionally high F-value of 1218.81 and a p-value of < 0.0001, signifying its critical role in enhancing arsenic adsorption. Reaction time (C) also significantly affected arsenic removal ($p = 0.0007$), suggesting that sufficient contact time is essential for achieving high removal efficiency. In contrast, pH (B) had an insignificant effect ($p = 0.9767$), indicating that within the tested range, changes in pH did not meaningfully impact the adsorption process. Interaction terms (AB, AC, and BC) were also not statistically significant, suggesting minimal synergistic effects between the variables. Among the quadratic terms, B^2 (pH) and C^2 (reaction time) were significant ($p = 0.0002$ and < 0.0001, respectively), revealing that non-linear relationships exist for these variables, particularly at higher or lower levels. The non-significant lack of fit (p = 0.7829) confirms that the model adequately fits the experimental data without substantial unexplained variation. These results highlight that optimizing dosage and reaction time is critical for maximizing arsenic removal, while pH has a negligible effect under the tested conditions.

An empirical correlation between arsenic removal efficiency, and three key factors was developed using the Box–Behnken design. A reduced cubic model with an R² of 0.996 was fitted for the process, indicating strong predictive accuracy.

$$\begin{aligned} As_{(removal)} &= 88.62 + 11.74A + 0.0076B + 1.80C + 0.2159AB \\ &\quad - 0.7588AC - 0.4378BC - 0.1163A^2 - 1.76B^2 - 3.67C^2 \end{aligned} \tag{1}$$

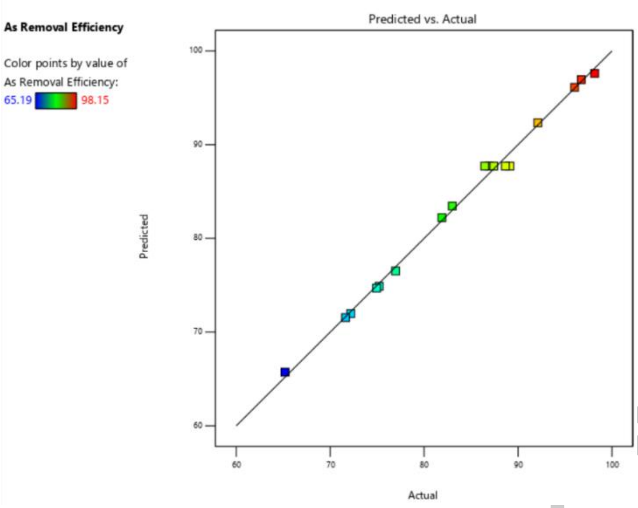


Figure 2. Comparison of actual experimental with model-predicted percent of the adsorption process.

Figure 2 illustrates the scatter plot comparing the experimentally observed arsenic removal efficiencies with the values predicted by the response surface methodology (RSM) model for the TiO_2-impregnated laterite adsorption system. The data points exhibit a strong alignment along the 45-degree reference line, indicating a high degree of agreement between the actual and predicted results. This strong correlation suggests that the developed RSM model reliably captures the behavior of the system across a range of experimental conditions. The distribution of color-coded points, representing removal efficiencies ranging from 65.19% to 98.15%, further demonstrates the model's ability to account for performance variability under different operational settings. Overall, the close fit between observed and predicted values affirms the model's accuracy, robustness, and effectiveness as a predictive tool for optimizing arsenic adsorption parameters.

3.2. Effect of operating parameters on arsenic removal using TiO_2-Impregnated Laterite

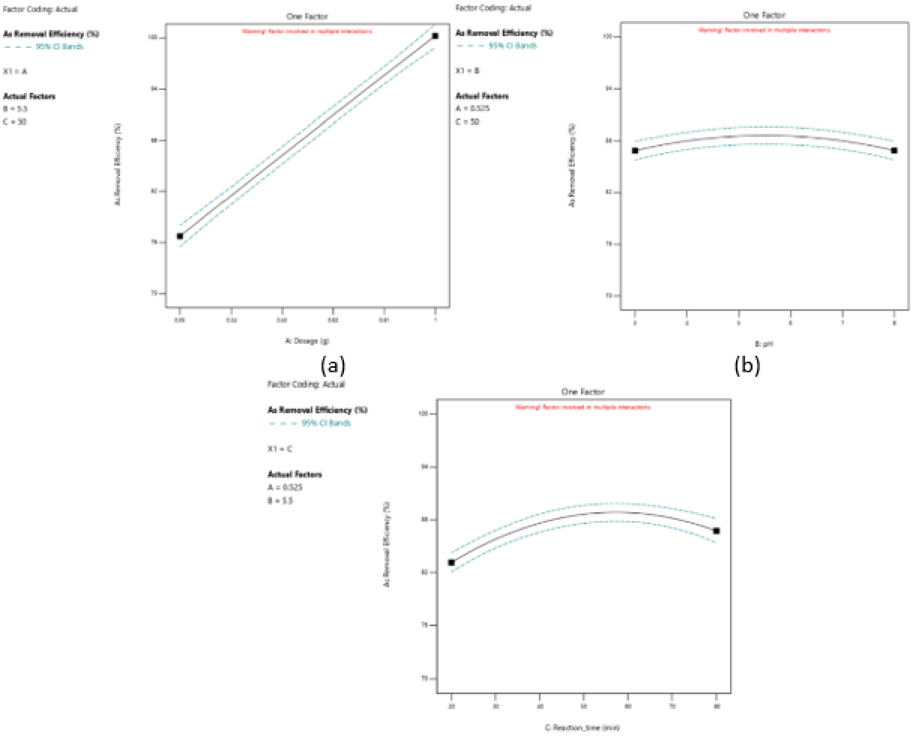
Percent arsenic removal in response to variations in operating parameters is shown in **Figure 3**.

Figure 3 depicts the individual effects of (a) adsorbent dosage, (b) solution pH, and (c) reaction time on the efficiency of arsenic removal using TiO_2-impregnated laterite, based on actual experimental levels. Among these variables, dosage (**Figure 3a**) was the most influential, showing a nearly linear increase in removal efficiency as the adsorbent mass rose from 0.01 g to 1.0 g. This strong dependence indicates that greater dosages enhance the available surface area and density of reactive hydroxyl groups, thereby providing more active sites for both arsenate adsorption and arsenite oxidation. The presence of TiO_2 likely accelerates this process by generating surface hydroxyl radicals under light exposure, which can oxidize As(III) to As(V), subsequently adsorbed via inner-sphere complexation onto Fe–O and Ti–O sites. The effect of solution pH (**Figure 3b**) was less pronounced, following a mild parabolic trend with maximum efficiency near pH 5.5. Mechanistically, this behavior can be explained by the interplay between the surface charge of the TiO_2–laterite composite and the speciation of arsenic oxyanions. Around pH 5–6, the surface is positively charged due to protonation of surface hydroxyl groups, favoring electrostatic attraction with negatively charged $H_2AsO_4^-$ species. At higher pH values, deprotonation of surface hydroxyls leads to electrostatic repulsion, while at very low pH, competition from excess protons may suppress arsenate adsorption. Reaction time (**Figure 3c**) exhibited a curved response, with efficiency increasing until about 50 minutes before leveling off, suggesting that adsorption–oxidation equilibrium had been reached. The initial rapid uptake reflects fast external surface adsorption and photocatalytic oxidation of As(III), followed by a slower diffusion-controlled stage where arsenic species migrate into mesopores or interact with less accessible active sites. Taken together, the results point to a synergistic adsorption–oxidation mechanism: (i) As(III) is oxidized to As(V) through photocatalysis on TiO_2, (ii) both As(III) and As(V) form surface complexes with Fe–O and Ti–O groups via ligand exchange, and (iii) electrostatic interactions modulate removal efficiency depending on solution pH. Among the tested parameters, adsorbent dosage exerts the strongest control, followed by reaction time and pH, highlighting the crucial role of active site density and surface chemistry in governing arsenic remediation using TiO_2-impregnated laterite.

3.3. Optimum points for arsenic removal

The 3D surface plots of the two parameter interaction effects of Dosage, pH, Reaction time on percent arsenic removal using TiO_2-Impregnated Laterite were shown in **Figure 4.**

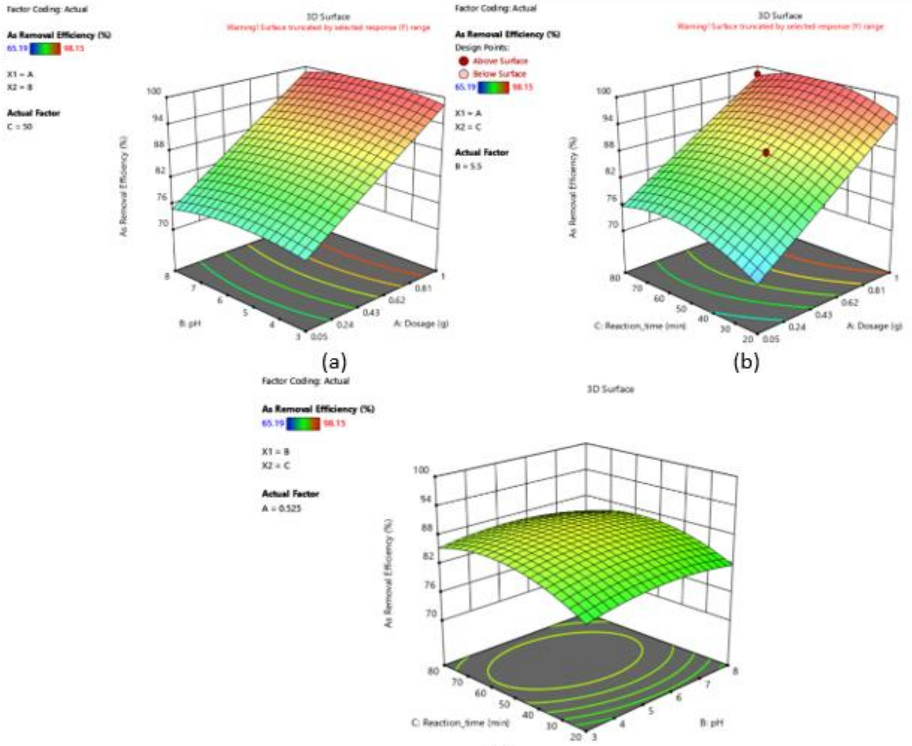
Figure 4 displays the three-dimensional surface plots that illustrate the interactive effects of adsorbent dosage, pH, and reaction time on arsenic removal efficiency using TiO_2-impregnated laterite. In **Figure 4a**, removal efficiency increases with dosage up to approximately 0.8 g, particularly under lower pH conditions, indicating that acidic environments enhance the oxidative adsorption process. However, beyond pH 6, a slight reduction in efficiency is observed, likely due to diminished electrostatic attraction or surface charge effects at higher pH levels. **Figure 4b** reveals a synergistic interaction between dosage and reaction time, with removal efficiency rising progressively as both parameters increase, reaching a maximum at the highest dosage tested. This trend highlights the combined importance of adequate adsorbent quantity and sufficient contact time for optimal arsenic removal. In **Figure 4c**, the interaction between pH and reaction time shows that maximum removal occurs at intermediate pH values (around 5–6) and extended contact durations (60–70 minutes), suggesting that favorable chemical conditions must align with appropriate reaction kinetics. Collectively, these surface plots underscore the complex, non-linear interactions among process variables and emphasize the need for integrated parameter optimization to achieve high arsenic removal efficiency.



(a) (b)

(c)

Figure 3. Effect of (a) Dosage (b) pH (c) Reaction time on arsenic removal using TiO_2-Impregnated Laterite.



(a) (b)

(c)

Figure 4. 3D surface plots of the two parameter interaction effects of Dosage, pH, Reaction time on percent arsenic removal using TiO_2-Impregnated Laterite: (a) Dosage and pH, (b) Dosage and Reaction time, (c) pH and Reaction time.

Table 3. The optimum condition for arsenic removal using TiO_2-Impregnated Laterite

Values of optimum conditions	Dosage (g)	0.99
	pH	5.3
	Reaction time (min)	71
Actual and predicted values of PCT removal	Actual	97.65%
	Predicted	98.82%
	Difference	1.17

The optimization results for arsenic removal using TiO_2-impregnated laterite, presented in **Table 3**, demonstrate the high effectiveness of the process under the identified optimal conditions. The optimal parameters were determined to be an adsorbent dosage of 0.99 g, a solution pH of 5.3, and a reaction time of 71 minutes. Under these conditions, the experimentally observed arsenic removal efficiency was 97.65%, closely aligning with the model-predicted value of 98.82%, yielding a minimal deviation of only 1.17%. This close agreement between predicted and actual outcomes affirms the precision and reliability of the response surface methodology (RSM) model applied in this study. The findings further underscore the strong adsorption performance of TiO_2-impregnated laterite, particularly in slightly acidic conditions, which likely enhance surface reactivity and improve the availability of active binding sites. Overall, these results validate the predictive capability of the model and reinforce the potential of TiO_2-impregnated laterite as an effective, low-cost adsorbent for arsenic removal in aqueous treatment applications.

4. Conclusion

This study confirmed the potential of TiO_2-impregnated laterite as an efficient and low-cost adsorbent for the removal of arsenic from aqueous solutions. Using a Box–Behnken Design within the Response Surface Methodology framework, the effects of three key operational parameters—adsorbent dosage, pH, and reaction time—were systematically investigated and optimized. The statistical performance evaluation using ANOVA and quadratic modeling highlighted the significant influence of dosage and reaction time, with a well-fitted model ($R^2 = 0.996$), confirming the predictive strength of the methodology. The findings indicated that both adsorbent dosage and reaction time significantly influenced arsenic removal efficiency, whereas pH had a comparatively minor effect within the studied range. Optimal conditions for maximum arsenic removal (98.82%) were identified at a dosage of 0.99 g (~1.0 g), pH 5.3, and a reaction time of 71 minutes, demonstrating the promise of TiO_2-modified laterite for real-world water treatment applications. This obtained removal efficiency of TiO_2-impregnated laterite is higher than that of $KMnO_4$-modified laterite (93.2%) and comparable to commercial adsorbents such as activated alumina (~95%), indicating superior or equivalent performance. Given the abundance and low cost of laterite, combined with the stability of TiO_2, the proposed material is well-suited for decentralized arsenic remediation systems, especially in rural or resource-constrained regions.

Despite the promising findings, several limitations warrant consideration. The experiments were performed under controlled laboratory conditions using synthetic arsenic-contaminated water, which may not fully represent the complexity of natural systems where multiple competing ions and organic matter coexist. Additionally, the long-term stability and reusability of the TiO_2-impregnated laterite were not assessed, leaving uncertainties about its durability and regeneration potential under repeated use. The investigation was also confined to a relatively narrow pH range, limiting the ability to predict performance in highly acidic or alkaline environments often encountered in field applications. Furthermore, adsorption isotherms and kinetic studies were not included, and these will be addressed in future work to provide deeper mechanistic insights into the removal process.

Future studies will focus on field-scale evaluations under diverse environmental conditions, particularly in arsenic-impacted areas. Further investigations should address the impact of co-existing contaminants, assess regeneration performance, and conduct life-cycle analyses to determine overall sustainability. Comprehensive material characterization is also recommended to elucidate surface modification effects and adsorption mechanisms. Additionally, the integration of TiO_2-impregnated laterite into hybrid treatment systems—such as those combining electrocoagulation or membrane technologies—could be explored to enhance removal efficiency and operational robustness.

Author contributions

L.P.T (PhD) and V.T.K.O (Master) conducted all the experiments and simulation and wrote the manuscript. L.P.T (PhD) revised the manuscript.

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