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Multivariate analysis and principal component analysis-based interpretation of arsenic removal dynamics from contaminated water using potassium permanganate-treated laterite

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ABSTRACT

Arsenic contamination in water resources poses a serious environmental and public health challenge because of its toxicity, persistence, and widespread occurrence in groundwater systems. Among various treatment technologies, adsorption using modified natural materials has attracted increasing attention due to its low cost, operational simplicity, and high removal efficiency. In this study, the arsenic removal performance of potassium permanganate-treated laterite (PPTL) was investigated under different operational conditions, and principal component analysis (PCA) was applied to interpret the multivariate relationships governing the adsorption process. Synthetic arsenic-contaminated wastewater with an initial concentration of 100 ppb was treated using PPTL under varying pH values, adsorbent masses, and interaction times. Descriptive statistics, correlation analysis, and PCA were performed using standardized datasets. The experimental results showed that arsenic removal efficiency ranged from 63.99% to 92.28%, with the highest removal achieved at pH 9, adsorbent mass of 1 g, and interaction time of 45 min. Correlation analysis revealed that adsorbent mass exhibited the strongest positive correlation with removal efficiency ($r = 0.948$). PCA results demonstrated that the first two principal components explained 88.14% of the total dataset variance, indicating that the PCA model effectively represented the adsorption system. PC1 was strongly associated with adsorbent mass and removal efficiency, whereas PC2 mainly reflected the influence of pH and interaction time. The findings confirm that adsorbent availability was the dominant factor controlling arsenic adsorption dynamics. Furthermore, the study demonstrates that PPTL is a promising low-cost adsorbent for arsenic-contaminated water treatment and highlights the effectiveness of PCA for interpreting complex environmental treatment datasets.

Keywords: arsenic removal, principal component analysis, potassium permanganate-treated laterite, adsorption, multivariate analysis.

INTRODUCTION

Arsenic contamination in water resources has become one of the most serious global environmental and public health concerns due to its high toxicity, persistence, and widespread occurrence in groundwater and surface water systems. Naturally occurring geological weathering, mining activities, metallurgical industries, pesticide application, coal combustion, and industrial wastewater discharge are recognized as major contributors to arsenic pollution worldwide (Smedley and Kinniburgh, 2002; Mohan and Pittman, 2007). According to the World Health Organization, the recommended maximum arsenic concentration in drinking water is 10 μg/L; however, arsenic concentrations exceeding 50–500 μg/L have been reported in many contaminated regions, particularly in South and Southeast Asia (WHO, 2022). It has been estimated that more than 140 million people in over 70 countries are exposed to arsenic-contaminated drinking water above the recommended safety limit (Ravenscroft et al., 2009).

Long-term arsenic exposure has been strongly associated with severe health disorders, including skin diseases, neurological impairment, cardiovascular complications, diabetes, and various

cancers. Recent epidemiological studies have confirmed that chronic arsenic exposure remains a major public health issue in many developing countries where groundwater is extensively used for domestic consumption (Chen et al., 2009; Podgorski and Berg, 2020).

To address this issue, numerous treatment technologies have been developed for arsenic removal, including coagulation–flocculation, membrane filtration, ion exchange, electrochemical oxidation, and adsorption processes. Among these methods, adsorption continues to receive considerable attention because of its operational simplicity, low cost, high efficiency, and suitability for decentralized treatment systems (Fu and Wang, 2011; Nicomel et al., 2015). Recent studies have demonstrated that adsorption systems using modified mineral adsorbents can achieve arsenic removal efficiencies exceeding 90% under optimized operational conditions (Nicomel et al., 2015; Alka et al., 2020; Al-Abbasi et al., 2026).

Natural mineral-based materials have increasingly been explored as sustainable adsorbents because of their abundance, low environmental impact, and strong adsorption potential. Laterite, an iron- and aluminum-rich material widely distributed in tropical regions, has shown promising performance for arsenic adsorption owing to its high iron oxide content and porous structure. Recent investigations reported that modified laterite materials could achieve arsenic removal efficiencies ranging from approximately 70% to more than 95%, depending on adsorbent dosage, pH conditions, and surface modification methods (Maiti et al., 2007; Asere et al., 2019; Elmakki et al., 2025). Surface modification using potassium permanganate ($KMnO_4$) has been found to significantly improve adsorption capacity by enhancing surface oxidation, increasing manganese oxide functional groups, and generating additional active adsorption sites.

Environmental adsorption processes are generally governed by multiple interacting operational variables, including pH, adsorbent dosage, interaction time, temperature, and contaminant concentration. Consequently, multivariate statistical techniques are increasingly applied to interpret complex environmental datasets and identify dominant operational factors. Principal component analysis (PCA) has become one of the most widely used statistical approaches for dimensionality reduction, pattern recognition, and interpretation of environmental treatment systems (Jolliffe, 2002). More recent applications have demonstrated that PCA can effectively explain over 80–90% of total variance in environmental adsorption and water quality datasets while identifying the major variables controlling treatment efficiency (Varol, 2020; Shrestha and Kazama, 2007).

Despite the growing number of studies investigating arsenic adsorption using modified adsorbents, limited attention has been given to the multivariate statistical interpretation of arsenic removal dynamics using Potassium Permanganate-Treated Laterite. Most previous research has primarily focused on adsorption efficiency, equilibrium behavior, and kinetic modeling, while the complex interactions among operational variables have not been comprehensively evaluated. In this context, the present study was conducted to investigate the arsenic removal performance of Potassium Permanganate-Treated Laterite under different operational conditions. Specifically, the study aimed to analyze the relationships among pH, adsorbent mass, interaction time, and arsenic removal efficiency, apply PCA to identify the dominant operational variables influencing adsorption performance, and interpret the multivariate interactions governing arsenic removal dynamics within the adsorption system.

RESEARCH METHODS

Preparation of arsenic-contaminated wastewater and potassium permanganate-treated laterite

Synthetic arsenic-contaminated wastewater was prepared by diluting a 500 ppm arsenic standard solution with tap water to obtain an initial arsenic concentration of 100 ppb. Approximately 5 L of solution was prepared for the adsorption experiments. Prior to treatment, the solution pH was adjusted to the desired experimental values using 0.1 M NaOH or 0.1 M HCl. Both initial and residual arsenic concentrations were determined using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to ensure accurate quantification of arsenic removal efficiency throughout the experiments.

Natural laterite was washed thoroughly with tap water and deionized water, dried at 105 °C for 24 h, crushed, and sieved to obtain particles of approximately 5 mm diameter. Surface modification

was performed using 0.1 mol/L $KMnO_4$ solution at a ratio of 100 mL solution per 10 g of laterite. The mixture was shaken at 150 rpm and 25 °C for 2 h to enhance surface oxidation and activate adsorption sites.

After modification, the laterite was filtered, repeatedly washed with deionized water until the rinsate became colorless, and dried again at 105 °C for 12 h. The prepared Potassium Permanganate-Treated Laterite (PPTL) was stored in airtight containers for subsequent arsenic adsorption experiments.

Experimental design

An experimental design approach was employed to evaluate the effects of three key operational variables on arsenic removal performance, including pH, adsorbent mass, and interaction time. These variables were selected because they are among the most influential factors affecting adsorption efficiency and adsorption equilibrium in arsenic treatment systems.

The experiments were conducted under different combinations of operational conditions to investigate the adsorption behavior of Potassium Permanganate-Treated Laterite and to generate a dataset suitable for multivariate statistical analysis and PCA. The investigated pH values ranged from acidic to alkaline conditions, while adsorbent mass and interaction time were varied to evaluate their influence on arsenic uptake efficiency. All adsorption experiments were conducted in triplicate, and the reported values represent mean results. Quality control procedures included instrument calibration using certified arsenic standards, blank sample analysis, and duplicate measurements to ensure analytical reliability.

The operational conditions and corresponding arsenic removal efficiencies are summarized in Table 1.

Statistical and PCA analysis

Descriptive statistics, correlation analysis, and PCA were performed using standardized datasets to evaluate the relationships among operational variables and arsenic removal efficiency. Data standardization was conducted prior to PCA in order to eliminate the influence of differences in variable scales and units, following commonly applied multivariate statistical procedures (Jolliffe, 2002; Abdi and Williams, 2010). The standardized data matrix was calculated using:

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{S_j} \quad (1)$$

where: Z_{ij} is the standardized value (z-score) of variable j for observation I, X_{ij} is the observed value, $\bar{X}_j$ is the mean value, S_j is the standard deviation.

The covariance matrix was calculated as:

$$C = \frac{1}{n-1} Z^T Z \quad (2)$$

where: C is the covariance matrix used for PCA, n represents the number of observations, Z is the standardized data matrix containing all standardized observations; Z^T is the transpose of the standardized matrix. Eigenvalues and eigenvectors were then computed to identify the principal components explaining the largest proportion of the total dataset variance. Principal components with eigenvalues greater than one were retained according to Kaiser's criterion (Kaiser, 1960). PCA has been widely applied in environmental studies for dimensionality reduction, pattern recognition, and identification of dominant operational variables in complex environmental systems (Shrestha and Kazama, 2007).

RESULTS AND DISCUSSION

Arsenic removal performance

Figure 1 illustrates the arsenic removal efficiencies obtained under different operational conditions involving variations in pH, adsorbent mass, and interaction time. The removal efficiency varied considerably, ranging from 63.99% to 92.28%, indicating that operational parameters significantly influenced the adsorption performance of Potassium Permanganate-Treated Laterite.

The highest arsenic removal efficiency (92.28%) was achieved at pH 9, an adsorbent mass of 1 g, and an interaction time of 45 min, whereas the lowest removal efficiency (63.99%) was observed at pH 5.5, an adsorbent mass of 0.01 g, and an interaction time of 10 min. These findings

Table 1. The operational conditions and Arsenic removal efficiencies

Run	pH	Adsorbent mass (g)	Interaction time (min)	Removal (%)
1	5.5	0.01	10	63.99
2	5.5	1	10	90.11
3	5.5	0.01	80	71.34
4	5.5	1	80	90.94
5	2	0.01	45	65.45
6	2	1	45	90.03
7	9	0.01	45	65.95
8	9	1	45	92.28
9	2	0.505	10	73.29
10	2	0.505	80	74.97
11	9	0.505	10	71.32
12	9	0.505	80	76.66
13	5.5	0.505	45	82.20

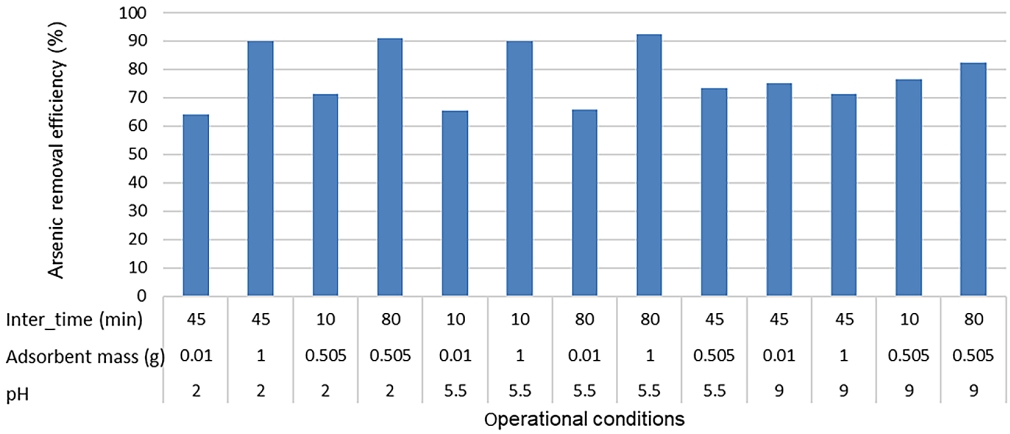

Figure 1. Arsenic removal efficiency under different operational conditions

indicate that adsorbent mass played a dominant role in controlling arsenic adsorption efficiency.

An increase in adsorbent mass substantially enhanced arsenic removal performance because of the greater availability of active adsorption sites and increased surface area for arsenic uptake. Similar observations have been widely reported in arsenic adsorption studies using iron-rich mineral adsorbents and modified natural materials (Maiti et al., 2007; Mohan and Pittman, 2007; Giri et al., 2021). Maiti et al. (2007) demonstrated that natural laterite achieved arsenic removal efficiencies ranging from approximately 60% to more than 90% with increasing adsorbent dosage under optimized conditions. Likewise, Al-Abbasi et al. (2026) emphasized that adsorbent dosage is one of the most influential operational parameters affecting arsenic adsorption because higher adsorbent mass increases the number of available reactive binding sites.

Interaction time also influenced adsorption performance, although its effect was less pronounced than that of adsorbent mass. Longer interaction periods moderately improved arsenic removal efficiency, likely because extended interaction time promoted diffusion of arsenic ions toward active adsorption sites and facilitated adsorption equilibrium attainment. Comparable adsorption kinetics have been reported in previous studies using mineral-based adsorbents and activated alumina systems (Singh and Pant, 2004; El-Rayyes et al., 2025). Singh and Pant (2004) observed that arsenic uptake increased rapidly during the initial adsorption stage before gradually approaching equilibrium conditions with increasing interaction time.

Although pH exhibited a relatively weaker influence compared with adsorbent mass, slightly higher removal efficiencies were generally observed under alkaline conditions. This behavior may be associated with changes in arsenic speciation and surface charge characteristics of the modified laterite, which can influence adsorption interactions under different pH environments.

Descriptive statistical analysis

Table 2 presents the descriptive statistical characteristics of the experimental variables used in the arsenic adsorption study, including pH, adsorbent mass, interaction time, and removal efficiency.

Arsenic removal efficiency exhibited an average value of 78.58%, with efficiencies ranging from 63.99% to 92.28%. The relatively high standard deviation of removal efficiency (10.21%) suggests substantial variability among the operational conditions, indicating that adsorption performance was strongly influenced by changes in pH, adsorbent mass, and interaction time. This variability also reflects the sensitivity of the adsorption process to operational parameter adjustments and highlights the importance of multivariate statistical analysis for identifying the dominant factors controlling arsenic removal performance.

To further evaluate the reliability and consistency of the experimental dataset, the coefficient of variation (CV) was calculated as the ratio between the standard deviation and the mean value. The CV for arsenic removal efficiency was approximately 13.0%, indicating moderate variability and acceptable experimental consistency. In environmental adsorption studies, CV values below 20% are commonly considered acceptable for experimental reproducibility (Everitt and Skrondal, 2010). Furthermore, the relatively narrow range between replicated central-point experiments suggests that the adsorption system exhibited stable operational behavior under intermediate conditions. These findings confirm that the experimental data are sufficiently reliable for subsequent multivariate statistical analysis and PCA interpretation.

Correlation analysis

The correlation matrix among the investigated variables is presented in Table 3.

The correlation analysis revealed that adsorbent mass exhibited the strongest positive relationship with arsenic removal efficiency, with a correlation coefficient of r=0.948. This strong association indicates that adsorbent mass was the dominant operational parameter influencing adsorption performance. The increase in adsorbent mass likely enhanced the availability of active adsorption sites and total surface area, thereby improving arsenic uptake efficiency.

Interaction time showed a moderate positive correlation with removal efficiency (r=0.356), suggesting that prolonged interaction time contributed to improved adsorption through enhanced diffusion and equilibrium attainment. In contrast, pH demonstrated a relatively weak correlation with arsenic removal efficiency (r=0.126), indicating that its direct influence on adsorption performance was less significant within the investigated experimental range.

Furthermore, the low correlations observed among the independent operational variables indicate minimal multicollinearity within the experimental dataset. This suggests that each operational parameter contributed independently to the adsorption process, thereby supporting the reliability of subsequent multivariate statistical analysis and PCA interpretation.

Principal component analysis

The PCA interpretation suggested that PC1 corresponded primarily to adsorption capacity-related factors, while PC2 represented operational equilibrium and kinetic influences. Meanwhile, PC3 and PC4 accounted for minor unexplained variability within the experimental system. The eigenvalues and explained variances of the principal components derived from the PCA are presented in Table 4.

The PCA results demonstrated that the first principal component (PC1) accounted for 61.74% of the total dataset variance, indicating that it represented the dominant source of variability within the adsorption system. Based on the loading matrix, PC1 was strongly associated with adsorbent mass and arsenic removal efficiency, suggesting that this component primarily reflected the adsorption capacity and general treatment performance of the Potassium Permanganate-Treated Laterite system. The high contribution of PC1 indicates that arsenic removal efficiency was mainly controlled by adsorbent availability and the number of active adsorption sites.

The second principal component (PC2) explained an additional 26.40% of the total variance, resulting in a cumulative variance of

Table 2. Descriptive statistics of variables

Variable	Mean	Standard deviation	Minimum	Maximum
pH	5.50	2.62	2	9
Adsorbent mass (g)	0.505	0.404	0.01	1
Interaction time (min)	45.00	26.31	10	80
Removal (%)	78.58	10.21	63.99	92.28

Note: The mean pH value was 5.50, with a standard deviation of 2.62, indicating that the experiments were conducted under a relatively broad acidic-to-alkaline range. The average adsorbent mass was 0.505 g, varying from 0.01 to 1 g, while the interaction time ranged from 10 to 80 min with a mean value of 45 min.

Table 3. Correlation matrix

Variable	pH	Adsorbent mass	Interaction time	Removal (%)
pH	1.000	0.000	0.000	0.126
Adsorbent mass	0.000	1.000	0.000	0.948
Interaction time	0.000	0.000	1.000	0.356
Removal (%)	0.126	0.948	0.356	1.000

88.14% for the first two components. PC2 was mainly associated with pH and interaction time, indicating that this component represented secondary operational influences related to adsorption equilibrium, diffusion processes, and arsenic speciation behavior under different chemical conditions. The relatively high cumulative variance explained by PC1 and PC2 demonstrates that the two-component PCA model effectively captured the majority of the information contained in the original dataset.

In contrast, the third principal component (PC3) accounted for only 8.23% of the total variance, indicating a comparatively weak contribution to the variability of the experimental system. PC3 likely represented minor variations or residual interactions among operational parameters that were not fully explained by the first two components. Similarly, the fourth principal component (PC4) contributed only 3.63% of the total variance, suggesting minimal influence on the adsorption behavior. The low contributions of PC3 and PC4 indicate that these components mainly reflected random variation or less significant operational effects within the dataset.

According to Kaiser's criterion, principal components with eigenvalues greater than 1 are considered statistically significant and suitable for interpretation (Jolliffe, 2002). In the present study, only PC1 and PC2 satisfied this condition, with eigenvalues of 2.47 and 1.06, respectively. Consequently, these two principal components were retained for further analysis and interpretation of arsenic adsorption dynamics.

Collectively, the dominance of PC1 confirmed that adsorption performance was primarily governed by adsorbent-related factors, whereas PC2 captured secondary operational interactions associated with pH and interaction time. The PCA results therefore provided a comprehensive multivariate interpretation of the arsenic removal process and effectively identified the dominant factors influencing adsorption efficiency.

PCA loading interpretation

The PCA biplot illustrating the relationships between the investigated variables and the first two principal components (PC1 and PC2) is presented in Figure 2.

Table 4. PCA eigenvalues and explained variance

Principal component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	2.47	61.74	61.74
PC2	1.06	26.40	88.14
PC3	0.33	8.23	96.37
PC4	0.15	3.63	100.00

The PCA loading analysis revealed that PC1 was strongly associated with adsorbent mass and arsenic removal efficiency, with loading values of 0.93 and 0.95, respectively. This strong positive relationship indicates that adsorbent mass was the dominant operational factor controlling the adsorption dynamics of arsenic removal by Potassium Permanganate-Treated Laterite. The high loading of removal efficiency on PC1 further confirms that adsorption performance was primarily governed by the availability of active adsorption sites provided by the adsorbent material.

In contrast, PC2 was mainly influenced by pH and interaction time, with loading values of 0.86 and 0.73, respectively. This finding suggests that these variables contributed to secondary variations in the adsorption process, particularly through their influence on adsorption equilibrium, diffusion behavior, and arsenic speciation under different chemical conditions.

The PCA biplot also demonstrated clear directional relationships among the variables. Adsorbent mass and removal efficiency were closely aligned along the positive PC1 axis, indicating strong positive correlation and similar contribution patterns. Meanwhile, pH and interaction time showed stronger associations with PC2, reflecting their combined influence on the physicochemical behavior of the adsorption system.

On the whole, the PCA results demonstrate that arsenic removal efficiency was predominantly controlled by adsorbent availability, while pH and interaction time acted as supporting operational factors affecting adsorption equilibrium and process kinetics. Similar PCA-based interpretations have been reported in environmental adsorption and water quality studies involving multivariate operational datasets (Shrestha & Kazama, 2007).

PCA-based interpretation of arsenic removal dynamics

The PCA biplot analysis provided a comprehensive visualization of the relationships among operational variables and arsenic removal efficiency, allowing clear differentiation between high-performance and low-performance adsorption conditions. Experimental runs 2, 4, 6, and 8 were clustered along the positive direction of the PC1 axis because of their high arsenic removal efficiencies exceeding 90%. These runs were characterized by the highest adsorbent mass (1 g), indicating that adsorbent availability played a dominant role in controlling adsorption performance. In contrast, experimental conditions with low adsorbent mass (0.01 g) were distributed toward the negative side of the PC1 axis and generally exhibited arsenic removal efficiencies below 70%.

The PCA interpretation confirmed that adsorbent mass was the primary operational factor governing arsenic adsorption dynamics. Increasing adsorbent dosage enhanced the availability

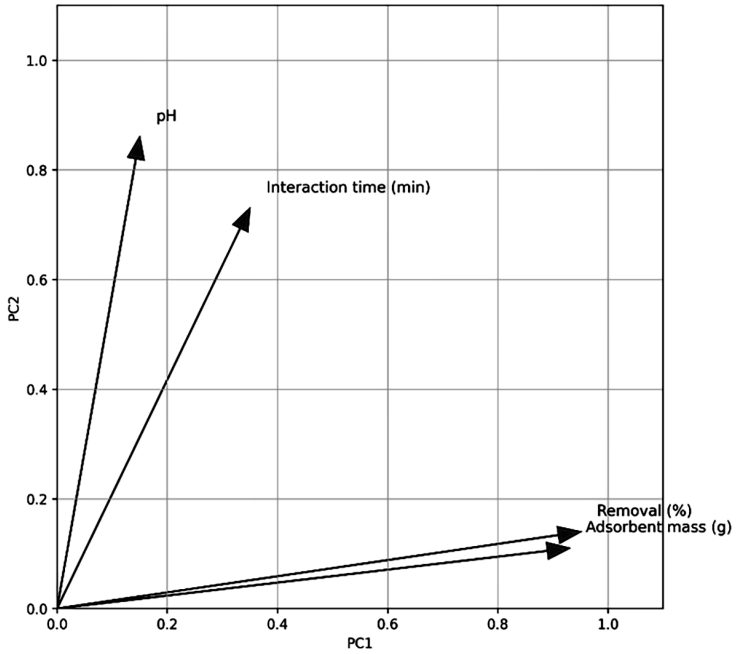

Figure 2. The PCA biplot (PC1 vs PC2)

of active adsorption sites and increased the total effective surface area for arsenic binding, thereby significantly improving adsorption efficiency. Similar trends have been reported in recent arsenic adsorption studies using iron-rich and manganese-modified mineral adsorbents. For instance, Giri et al. (2021) reported that modified mineral-based adsorbents achieved arsenic removal efficiencies exceeding 90% when adsorbent dosage was increased under optimized conditions. Likewise, Al-Abbasi et al. (2026) emphasized that adsorbent dosage is one of the most influential parameters controlling arsenic uptake because higher dosage increases the number of reactive adsorption sites and improves adsorption equilibrium capacity.

Interaction time exhibited a secondary but still important contribution to arsenic removal efficiency. Longer interaction periods moderately improved adsorption performance by promoting intraparticle diffusion and facilitating equilibrium attainment between arsenic species and the adsorbent surface. Similar adsorption kinetics were reported by El-Rayyes et al. (2025), who observed that arsenic uptake increased rapidly during the initial adsorption stage before gradually stabilizing as equilibrium conditions were approached.

Although pH demonstrated a relatively weaker direct correlation compared with adsorbent mass, slightly improved adsorption efficiencies were generally observed under alkaline conditions. This behavior may be associated with changes in arsenic speciation, surface charge distribution, and electrostatic interactions between arsenic ions and iron–manganese oxide functional groups on the modified laterite surface. Recent studies have similarly highlighted the important role of pH in controlling adsorption mechanisms and arsenic speciation behavior in aqueous systems (Podgorski and Berg, 2020; Al-Abbasi et al., 2026).

Taken together, the PCA approach proved highly effective for simplifying the interpretation of complex environmental treatment datasets and identifying the dominant operational variables influencing arsenic adsorption dynamics. By reducing multidimensional experimental information into a limited number of principal components, PCA enabled clearer visualization of variable interactions, adsorption behavior, and treatment performance patterns. Recent environmental studies have also demonstrated that PCA is a powerful multivariate statistical tool for identifying controlling factors and optimizing adsorption and water treatment systems (Varol, 2020; Giri et al., 2021).

CONCLUSIONS

This study successfully evaluated the arsenic removal performance of potassium permanganate-treated laterite (PPTL) under different operational conditions and applied PCA to interpret the multivariate relationships governing the adsorption process. The experimental results demonstrated that arsenic removal efficiency varied from 63.99% to 92.28%, depending on pH, adsorbent mass, and interaction time. The highest removal efficiency (92.28%) was achieved at pH 9, an adsorbent mass of 1 g, and an interaction time of 45 min, confirming the strong adsorption potential of the modified laterite material.

Correlation analysis and PCA consistently identified adsorbent mass as the dominant operational parameter controlling arsenic adsorption efficiency. The strong positive correlation between adsorbent mass and removal efficiency ($r = 0.948$) indicated that increasing adsorbent dosage significantly enhanced arsenic uptake because of the greater availability of active adsorption sites and adsorption surface area. PCA results further showed that the first principal component (PC1) explained 61.74% of the total dataset variance and was primarily associated with adsorbent mass and removal efficiency, while the second principal component (PC2) explained 26.40% of the variance and mainly reflected the influence of pH and interaction time. Collectively, PC1 and PC2 explained 88.14% of the cumulative variance, demonstrating that the PCA model effectively represented the multidimensional adsorption dataset.

The PCA biplot interpretation successfully differentiated high-performance and low-performance adsorption conditions and provided clear visualization of the interactions among operational variables. The findings confirmed that adsorbent availability primarily governed arsenic removal dynamics, whereas pH and interaction time contributed secondary effects related to adsorption equilibrium, diffusion behavior, and arsenic speciation. These results demonstrate the usefulness of PCA as a powerful multivariate statistical tool for simplifying complex environmental treatment datasets and identifying the dominant factors influencing adsorption systems.

The study highlights the potential applicability of Potassium Permanganate-Treated Laterite as an effective and low-cost adsorbent for arsenic-contaminated water treatment. The integration of adsorption experiments with multivariate

statistical analysis provides valuable insight into operational optimization and environmental treatment dynamics. Future studies should further investigate adsorption isotherms, kinetic modeling, regeneration capacity, and the application of the modified laterite under real wastewater conditions to support large-scale practical implementation.

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