DRINKING WATER TREATMENT SLUDGE AS AN EFFECTIVE ADSORBENT FOR LINEAR ALKYLBENZENE SULFONATE FROM SYNTHETIC SOLUTIONS

B. M. C. N. Dissanayake, K. G. Jayalath* and P. K. Adhihetty
Department of Chemistry, Faculty of Natural Sciences, The Open University of Sri Lanka, Sri Lanka

Drinking water treatment sludge, a byproduct of the coagulation process in water purification plants, offers potential for sustainable reuse in environmental remediation. This study investigates alum sludge as a cost-effective adsorbent for removing Linear Alkylbenzene Sulfonate (LAS), a common anionic surfactant in laundry wastewater. Due to its persistence and toxicity, improper discharge of LAS poses serious ecological risks. This study proposes an eco-friendly approach by repurposing waste sludge to eliminate such pollutants. Characterization studies of sludge showed a loamy sand texture with a pH of 7.42 ± 0.06, bulk density of 0.64 ± 0.1 g/cm^3, particle density of 2.00 ± 0.4 g/cm^3, porosity of 0.68 ± 0.1, and point of zero charge (PZC) of 6.60 ± 0.04. Batch adsorption studies were conducted using the Methylene Blue Active Substances (MBAS) method to evaluate LAS removal under varying particle sizes, sludge dosages, contact times, and pH levels. Fine particles (<0.5 mm) achieved the highest removal efficiency (47.04 ± 1.32%), while coarser particles (>3.2 mm) were less effective. Adsorption efficiency increased with higher sludge-to-solution ratios, peaking at 99.52% at a 1:2 ratio; beyond this, no significant improvement occurred. Contact time studies found optimal removal (99.49 ± 0.20%) at 60 minutes, after which equilibrium was reached. Lower pH (acidic pH) favored the adsorption process, and adsorption data fit the Langmuir isotherm model, suggesting monolayer surface coverage. These results highlight the potential of alum sludge in removing LAS from contaminated water, providing a low-cost, sustainable alternative to traditional adsorbents. The study supports waste valorization and lays the groundwork for eco-friendly surfactant removal methods using readily available industrial byproducts.

Keywords: Alum Sludge, adsorption, laundry wastewater, wastewater treatment,

**Corresponding Author: jijay@ou.ac.lk*

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INTRODUCTION

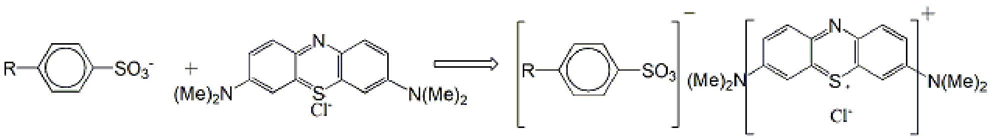
Drinking water treatment with aluminium-based coagulants produces large volumes of alum sludge as a byproduct. Recent studies highlight environmental challenges associated with alum sludge disposal, especially when using conventional methods such as landfilling, open dumping, or discharge into water bodies (Babatunde et al., 2008; Pająk, 2023). These practices can lead to secondary pollution, increased landfill load, and long-term ecological risks. Several studies suggests that a more sustainable and environmentally friendly approach is to reuse alum sludge as a low-cost adsorbent for pollutant removal in wastewater treatment. Surfactants, particularly Linear Alkylbenzene Sulfonates (LAS), are widely used in household and industrial detergents and frequently enter domestic wastewater, where they contribute to foam formation, oxygen depletion, and toxicity to aquatic life. According to several studies, adsorption is an effective and widely used method for removing such surfactants from water. Materials such as activated carbon have demonstrated high efficiency in this process; however, their cost limits large-scale use (Badmus et al., 2021). Therefore, this study was focused on investigating the potential of alum sludge as an economical alternative adsorbent for LAS removal. The objectives include characterizing the physicochemical properties of the sludge, evaluating its adsorption capacity using the MBAS method (APHA, 2023). Optimizing key operational parameters such as particle size and pH and examining the adsorption mechanisms through desorption studies and thermodynamic analysis. Through this approach, the study aimed to assess the feasibility of utilizing alum sludge as a sustainable and eco-friendly material for wastewater treatment applications.

METHODOLOGY

Alum sludge used in this study was collected from a local drinking water treatment plant. The sludge was air-dried and then oven-dried to remove moisture before being characterized by its key physical and chemical properties. These included moisture content, pH, bulk density, porosity, texture, and the point of zero charge (PZC), which are critical factors influencing adsorption behavior.

A blank test was conducted to determine background LAS in the alum sludge prior to adsorption experiments, any native LAS was considered negligible if below the method to detection limit. To optimize the removal of linear alkylbenzene sulfonate (LAS) from aqueous solutions, four major operational parameters were investigated: particle size, sludge dosage, contact time, and solution pH. Five particle size fractions, ranging from less than 0.5 mm to greater than 3.2 mm, were evaluated to determine the size range with the highest adsorption efficiency. Using the most effective particle size, the sludge-to-solution ratio was varied from 1:2 to 1:6, as no residual solution was observed at the initial 1:1 ratio The experiment was conducted under controlled conditions at room temperature (27 ± 1 °C), with a fixed shaking duration of one hour to simulate mixing.

To determine the equilibrium time for LAS adsorption, contact times of 15, 30, 45, 60, and 90 minutes were studied. The influence of pH was examined across a range



Anionic Surfactant Methylene Blue Ionic Complex

Furthermore, to understand the adsorption mechanism, a series of LAS solutions with concentrations ranging from 0.5 to 5 mg/dm³ were treated with a fixed dose of alum sludge. The adsorption capacity of each solution was measured using the following equation:

$$q_e = \frac{(C_0 - C_e)\,V}{m}$$

Where:

q_e = Adsorption capacity (mg/g)

C_0 = Initial concentration of LAS (mg/L)

C_e = Equilibrium concentration of LAS (mg/L)

V = Volume of solution (L)

M = Mass of adsorbent (g)

After equilibrium was reached, the experimental data were analyzed using both Langmuir and Freundlich isotherm models. This analysis helped to determine whether the adsorption process followed a monolayer (chemical) or multilayer (physical/heterogeneous) mechanism, providing insights into the nature and efficiency of LAS removal by alum sludge.

RESULTS AND DISCUSSION

Characterization results of alum sludge are given in Table 1.

Table 1 Summary of Alum Sludge Characteristics

Property	Description
Color	Grayish white
Texture	Loamy sand with sand (83%), silt (16 %), and clay (1%)
Bulk density	0.64 ± 0.10 g/cm³
Particle density	2.00 ± 0.40 g/cm³
Porosity	0.68 ± 0.10
pH	7.42 ± 0.06
Point of Zero Charge (PZC)	6.60 ± 0.04

The blank test confirmed that alum sludge contained only trace levels of LAS, which were considered negligible for the adsorption study. The effectiveness of alum sludge in removing linear alkyl benzene sulfonate (LAS) from aqueous solution was first evaluated using an untreated detergent solution. A noticeable reduction in adsorption was observed after treatment, indicating a significant reduction in LAS concentration ($30.3 \pm 4.3\%$). This confirms the strong adsorption potential of alum sludge for eliminating anionic surfactants. The promising initial results led to further optimization of key adsorption parameters to improve removal efficiency.

Adsorption parameters were subsequently optimized, as presented in Figure 1. Among the tested particle sizes, fine particles (<0.5 mm) exhibited the highest adsorption capacity ($47.0 \pm 1.3\%$), whereas larger particles (>3.2 mm) demonstrated significantly lower adsorption capacity ($13.8 \pm 2.6\%$). This is attributed to the increased surface area and porosity of smaller particles, offering more active binding sites (positively charged metal hydroxides in DWTS) for SO^{3-} in LAS. One-way ANOVA *($p<0.05$)* confirmed that particle size significantly influences adsorption performance, with a clear correlation between reduced particle size and increased efficiency.

Similarly, increasing the sludge-to-solution ratio positively influenced LAS removal. As shown in Figure 2, adsorption reached nearly complete removal ($99.5 \pm 0.1\%$) at a 1:2 ratio (50 g sludge per 100 mL solution). Beyond this point, the removal rate plateaued, suggesting saturation of available adsorption sites. Adding more sludge did not improve performance and may lead to inefficiency, especially in large-scale applications.

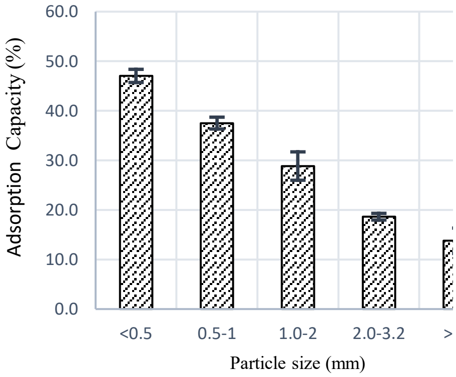


Figure 1:Adsorption capacity with different sludge particle sizes

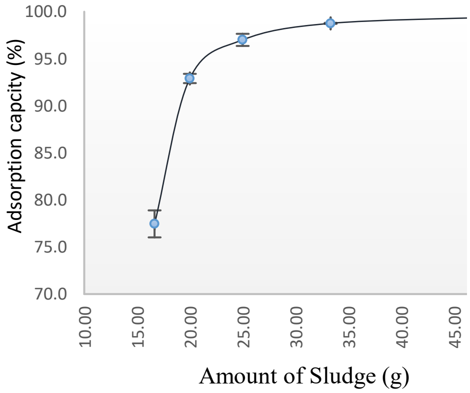


Figure 1: Adsorption capacity with different amounts of sludge (0 mm < 3.2 mm)

The influence of shaking time was evaluated up to 90 minutes (Figure 3). Adsorption efficiency increased to 60 minutes, reaching 99.5 ± 0.2 %, after which it remained stable. This indicates that 60 minutes is the optimal contact time, ensuring sufficient interaction without excess energy use. These findings highlight the importance of determining a suitable contact time for effective, energy-efficient treatment.

The effect of pH on LAS adsorption was also assessed. As shown in Figure 4, adsorption was most favorable under acidic conditions (90–98%) due to the positively or neutrally charged sludge surface, which enhances electrostatic attraction with the negatively charged sulfonate group ($–SO_3^-$) in LAS. At very low pH, however, excessive protonation may deactivate adsorption sites and affect long-term stability. Around the point of zero charge (pH ≈ 6), adsorption slightly decreased (92.72%), while at higher pH values, increasing surface negativity repels LAS, reducing adsorption to 59.34% at pH 8 and 43.34% at pH 10. These results confirm that acidic to mildly neutral pH conditions are most suitable for LAS removal with alum sludge.

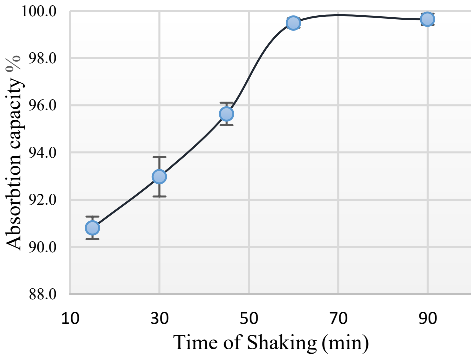


Figure 2: Adsorption capacity with different shaking times of sludge (< 3.2 mm) for a 1:2 sludge: solution ratio

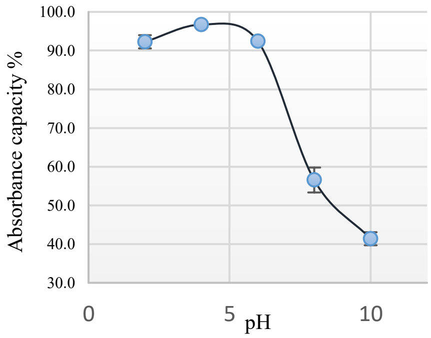
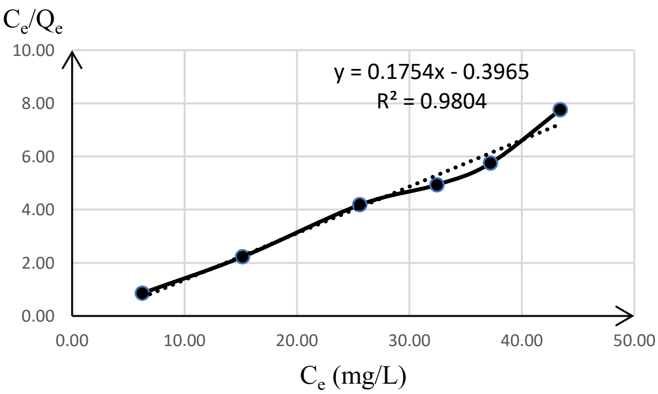


Figure 3: Effect of the pH on adsorption capacity

To understand the nature of the adsorption process, isotherm models were applied. The Langmuir isotherm, assuming monolayer adsorption on a homogenous surface with finite identical sites, provided the best fit (Figure 5). In contrast, the Freundlich model fit poorly, suggesting multilayer adsorption or adsorption on heterogeneous surfaces was not predominant. Thus, LAS adsorption by alum sludge is best described by monolayer coverage on uniform adsorption sites.



$$\frac{C_e}{q_e} = \frac{1}{Q_m b} \cdot C_e + \frac{1}{Q_m}$$

Figure 5: Langmuir Plot for LAS Adsorption onto DWTS

CONCLUSIONS

This study indicates that alum sludge is an effective and sustainable adsorbent for removing LAS from detergent solutions through the monolayer adsorption process. Maximum adsorption occurred under acidic conditions with fine particles (< 0.05 mm), a 1:2 sludge-to-solution ratio, and a 60-minute contact time.

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