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Application of chicken eggshell and coconut shell-based adsorbents for surfactant removal in laundry industry

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Abstract: The rapid growth of laundry services industry has increased the generation of wastewater containing linear alkylbenzene sulphonate (LAS), a surfactant that poses potential risks to aquatic environments. This study aims to assess the effectiveness of eggshell and coconut shell-based adsorbents for LAS removal in laundry wastewater and to determine the composition ratio and contact time resulting in the highest reduction of LAS. This study used the batch method to assess the effectiveness of the combined adsorbent, with LAS concentrations determined using the methylene blue active substances (MBAS) method through UV-Vis spectrophotometry at 652 nm. Five adsorbent percentage mass composition ratios (100:0, 75:25, 50:50, 25:75, and 0:100) were evaluated at contact times of 60, 90, 120, and 150 min. The result indicated that the chicken eggshell and coconut shell-based adsorbent was highly effective for LAS removal in laundry wastewater, achieving a high removal efficiency of 95.35% and an adsorption capacity of 0.156 $mg \cdot g^{-1}$. Moreover, the best variation that achieved the highest reduction of LAS levels in laundry wastewater was the 50%:50% ratio of carbonised chicken eggshell to coconut shell from a total of 20 g of adsorbent, with a contact time of 120 min. This high performance was attributed to the synergistic mechanisms involving physical adsorption by carbonised coconut shell-based activated carbon through van der Waals forces and hydrophobic interactions, along with chemical adsorption by chicken eggshells via ionic interactions between Ca^{2+} ions and sulphonate (SO_3^-) groups of LAS.

Keywords: adsorbent, chicken eggshell, coconut shell, laundry wastewater, linear alkylbenzene sulphonate (LAS), surfactant, wastewater management

INTRODUCTION

The rapid growth of laundry service industry in Indonesia reflects a shift toward a more practical and efficiency-based lifestyle. According to the Indonesian Laundry Association (Ind.: Asosiasi Laundry Indonesia), the sector has expanded at an average rate of 20% per year, driven not only by urban demand but also by increasing penetration into semi-urban and rural areas (Marifati and Ubaidillah, 2020). This trend has contributed to the rise of home-based laundry industry, including those in the Jebres District of Surakarta, Indonesia, where daily operations generate significant volumes of wastewater. High mobility around educational institutions, healthcare facilities, offices, and commercial centres further increases reliance on laundry services among students and workers with limited time for self-laundering. Consequently, the growing number of small-scale laundry businesses correlates with increasing wastewater discharge (Nugroho *et al.*, 2020).

Laundry wastewater typically contains pollutants derived from detergents, fabric softeners, and auxiliary chemicals. Surfactants serve as the primary active agents in detergents, while builders such as phosphates and additional additives are used to enhance cleaning performance (Cheng *et al*., 2020). Among these compounds, linear alkylbenzene sulphonate (LAS) is the most widely used anionic surfactant in domestic and commercial detergents due to its low production cost and strong cleaning efficiency (Faria *et al*., 2019; Mahmudah, Faizah and Munir, 2024). Although LAS is biodegradable, its degradation requires optimal environmental conditions and specific microorganisms such as *Bacillus* sp. and *Cladosporium resinae* (Suresh and Abraham, 2019). Natural degradation typically reaches only about 50% after nine days (Rizkiya *et al*., 2023). At elevated concentrations, LAS becomes toxic, disrupts aquatic ecological balance, damages cell membranes, and potentially leads to bioaccumulation (Daulay *et al*., 2022). Field measurements have reported LAS concentrations in laundry effluents ranging from 12,24 to 1.023,7 mg·dm^{-3} (Braga and Varesche, 2014). A study in Kebonsari, Surabaya, Indonesia documented a concentration of 18.32 mg·dm^{-3} (Herrari, Slamet and Purwanti, 2020). Likewise, wastewater from the Home Industry Laundry Klin & Klin in Jebres, Surakarta contained 22.07 mg·dm^{-3} of LAS, far exceeding the Central Java regional quality standard of 3.00 mg·dm^{-3}. These findings highlight the environmental risks posed by untreated or insufficiently treated laundry wastewater.

Despite these concerns, most home-based laundry businesses lack proper wastewater treatment facilities. Conventional wastewater treatment plants (WWTPs) are typically available only at industrial scales, while small-scale operators often discharge wastewater directly into drainage channels or natural water bodies without prior treatment (Afifah, Setyono and Rachmawati, 2024). This practice exacerbates pollution in densely populated residential areas such as Jebres, Surakarta, Indonesia. Several treatment approaches – including coagulation, flocculation, filtration, ozonation, and adsorption – have been investigated for surfactant removal (Delforno *et al*., 2020). Among them, adsorption is considered a promising method due to its operational simplicity, cost-effectiveness, and compatibility with natural and waste-derived adsorbents.

Chicken eggshells are an abundant yet underutilised organic waste material. For instance, Samarinda City, Indonesia, generated 307.22 Mg of eggshell waste in 2013, most of which ended up in landfills (Fitriyana and Safitri, 2015). Eggshells possess a microporous structure and high calcium carbonate ($CaCO_3$) content, enabling adsorption through both physical and chemical mechanisms (Li *et al.,* 2021). Previous studies have reported improved adsorption performance when eggshells are combined with other adsorbents, such as zeolite, yielding capacities higher than those of either material used individually (Listianti and Sutanto, 2024). Coconut shell activated carbon is another well-established adsorbent widely applied in wastewater treatment due to its high surface area, well-developed microporosity, and strong affinity for organic pollutants (Lukman, 2023). Its lignocellulosic composition facilitates pore formation during carbonisation and activation, producing a high-quality adsorbent capable of capturing dyes, surfactants, heavy metals, and various organic compounds (Gustinenda and Margo, 2017). Given these complementary characteristics, combining eggshell powder with coconut shell activated carbon presents a promising approach for developing an environmentally friendly and locally sourced adsorbent.

However, despite the potential synergy between these two materials, no studies have specifically examined their combined application for removing LAS from real laundry wastewater, particularly within small-scale home industry settings in Indonesia. Therefore, this study aims to assess the effectiveness of combined chicken eggshell and coconut shell-based adsorbents for LAS removal in laundry wastewater. Furthermore, to determine the composition ratio and contact time that result in the highest LAS reduction.

MATERIALS AND METHODS

RESEARCH DESIGN

This study used a laboratory-based experimental design (batch method) to assess the effectiveness of combined chicken eggshell and coconut shell-based adsorbents for linear alkylbenzene sulphonate (LAS) removal in laundry wastewater. Sampling technique based on SNI 6989.57:2008. The experimental work involved five adsorbent mass compositions with each tested at four contact times. Each treatment combination was performed in duplicate, resulting in a total of 40 experimental units. Adsorption performance was evaluated through effectiveness and adsorption capacity calculations. All replicate results were expressed as mean ±standard deviation to ensure measurement reliability and to assess variation among replicates.

Wastewater sample in this study were taken directly from the laundry discharge outlet (Home Industry Laundry X) located in Kartika, Jebres District, Surakarta, Central Java, Indonesia. Meanwhile, laboratory analysis was conducted at the Central Laboratory of Sebelas Maret University and Yogyakarta Public Health Laboratory. The sampling process and data analysis conducted from September to December 2025.

ADSORBENT PREPARATION AND ADSORPTION PROCEDURE

Chicken eggshell and coconut shell activated carbons were prepared as combined adsorbent materials prior to the adsorption experiments (Fig. 1). Eggshells were thoroughly washed, oven-dried at 110°C for 1 h, crushed, and sieved to obtain a particle size of 200 mesh. The processed material was carbonised at 600°C for 2 h and subsequently chemically activated by immersion in 0.75 M H_3PO_4 for 24 h. After activation, the material was rinsed with distilled water until neutral pH was achieved, oven-dried at 110°C for 3 h, and stored in a desiccator. Coconut shell activated carbon was produced through physical activation by heating at 600°C, followed by grinding and sieving to 200 mesh. The material was then cooled to room temperature and stored in a desiccator. Five adsorbent percentage mass composition ratios (w/w) of chicken eggshell and coconut shell activated carbon (100:0, 75:25, 50:50, 25:75, and 0:100) were prepared (Tab. 1). Afterward, 10 dm^3 of laundry wastewater was collected for the experiments.

All the adsorption experiment were conducted at room temperature (25 ±2°C). For each experimental run, 20 g of adsorbent was added to 200 cm^3 of laundry wastewater in an Erlenmeyer flask and agitated using an orbital shaker (250 rpm) to ensure adequate contact between the adsorbent and the solution. The adsorption process was conducted at contact times of 60, 90, 120, and 150 min. At the end of each contact period, the suspension was filtered using Whatman filter paper, and the

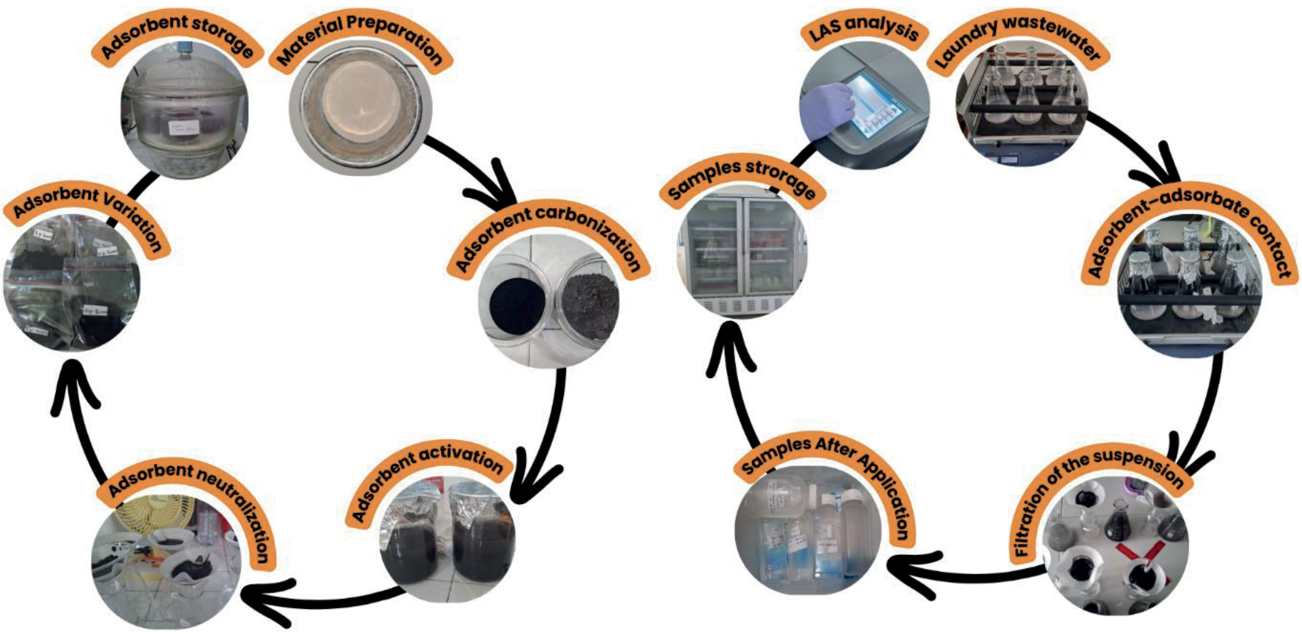

Fig. 1. Workflow for producing adsorbent (left) and asdorption procedure (right); source: own elaboration

Table 1. Adsorbent mass composition ratio

Sample symbol	Percentage mass ratio (eggshell AC: coconut shell AC)	Activated carbon (g)	
		mass of chicken eggshell	mass of coconut shell
A	100:0	20	0
B	75:25	15	5
C	50:50	10	10
D	25:75	5	15
E	0:100	0	20

Explanation: AC = activated carbon.
Source: own elaboration.

filtrate was collected for subsequent LAS analysis. Concentration of LAS in laundry wastewater samples was analysed following SNI 06-6989.51-2005 for anionic surfactants using the methylene blue active substances (MBAS) method with UV–Vis spectrophotometry at 652 nm.

DATA ANALYSIS

The analysis was conducted to quantify the performance of each adsorbent composition in removing LAS from laundry wastewater. The calculation of LAS concentrations was performed using the linear regression formula from the standard calibration curve. The formula is described as follows (Rachmawati *et al.*, 2024):

$$y = mx + c \tag{1}$$

where: y = the absorbance value of each standard solution, x = the concentration of linear alkylbenzene sulphonate (LAS) (mg·dm^{-3}), m = slope of the calibration curve, c = the constant obtained from the experimental analysis.

The coefficient of determination (R^2) of the calibration curve was used to assess the linearity of the calibration model.

Adsorption effectiveness was determined by comparing the initial LAS concentration (C_0) with the final concentration after treatment (C) using the Equation (2) (Kanwal *et al.*, 2024):

$$Ef = \frac{C_0 - C}{C_0} 100 \tag{2}$$

where: Ef = the adsorption effectiveness (%).

Adsorption capacity represents the amount of LAS removed per unit mass of adsorbent and is calculated as follows (Kanwal *et al.*, 2024):

$$q_e = \frac{(C_0 - C)\, V}{M} \tag{3}$$

where: q_e = adsorption capacity (mg·g^{-1}), V = volume of wastewater used in the experiment (dm^3), M = mass of adsorbent used (g).

All measurements were performed in duplicate, and the resulting data were expressed as mean ±standard deviation to assess analytical precision and variability among replicates. Data were tabulated and visualised to compare adsorption performance across adsorbent compositions and contact times.

RESULTS AND DISCUSSION

LAUNDRY WASTEWATER FROM LAUNDRY INDUSTRY

Wastewater samples were collected from a home laundry industry located in the densely populated Kartika area, Jebres, Surakarta, where the wastewater is discharged directly into the residential drainage system without prior treatment.

As shown in Figure 2, the wastewater has a turbid appearance, indicating the presence of dissolved and suspended materials such as residual detergent, dust, and fabric fibres produced during washing activities (Aprilia and Asyfiradayati, 2025). The samples also showed noticeable odour and foam formation. The pH of the laundry wastewater was generally alkaline (8–9) due to the presence of anionic surfactants and alkaline builders (Klimonda and Kowalska, 2025).

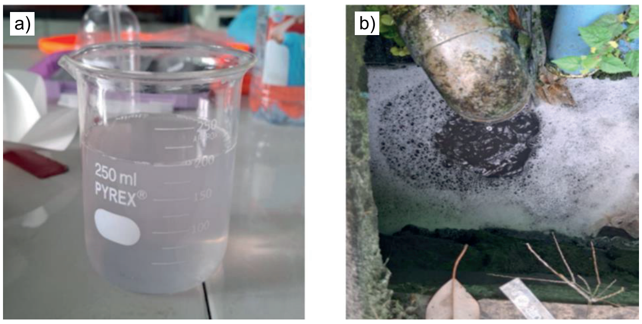

Fig. 2. Laundry wastewater; a) collected sample in a beaker glass, b) the actual discharge channel at the industrial site; source: author's own documentation

CONCENTRATION OF LINEAR ALKYLBENZENE SULPHONATE IN LAUNDRY WASTEWATER

The concentration of LAS in the laundry wastewater was determined spectrophotometrically by comparing absorbance values with a standard calibration curve, as shown in Figure 3.

The calibration produced a linear regression equation of $y = 0.3961x + 0.0003$, with an excellent linearity of $R^2 = 0.9999$, indicating good linearity within the studied concentration range (Delgado, 2022). The pre-treatment analysis indicated that the LAS concentration in the untreated laundry wastewater (control sample – K1 and K2) was relatively high, with an average value of 16.34 mg·dm^{-3} (Tab. 2), exceeding the regulatory limit of 3 mg·dm^{-3} set by the local government (Central Java Province, 2012). To ensure measurement precision, duplicate analyses were conducted, resulting in a standard deviation (*SD*) of 0.59 mg dm^{-3} and a relative standard deviation (*RSD*) of 3.64%. This values indicate low variability between duplicate measurements and acceptable analytical precision, as an *RSD* ≤ 5% is generally considered acceptable for quantitative analysis (Harris, 2015; Indryati *et al.*, 2023).

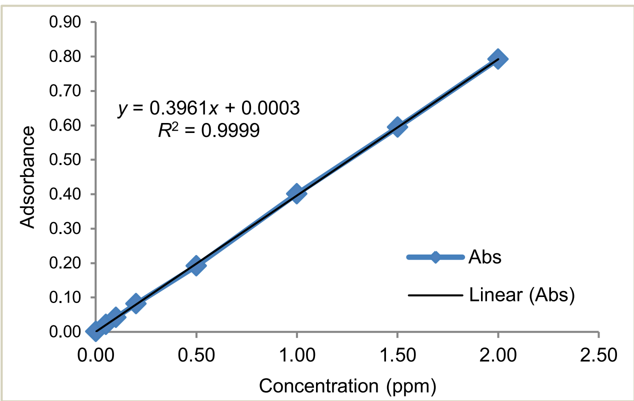

Fig. 3. Linear alkylbenzene sulphonate (LAS) calibration curve with the range of 0–2 ppm; $R^2 = 0.9999$; source: own study

Table 2. Concentration of linear alkylbenzene sulphonate (LAS) in laundry wastewater

Sample	Absorbance y	Concentration before correction x (mg·dm^{-3})	Dilution factor	Concentration x (mg·dm^{-3})
K1	0.664	1.67559	10×	16.76
K2	0.631	1.59227	10×	15.92
Mean (x)				16.34
Standard deviation (*SD*)				0.59
Relative standard deviation *RSD* (%)				3.64

Explanation: K1, K2 = control samples.
Source: own study.

The high levels of LAS surfactants detected in laundry wastewater reflect their extensive use as the main active ingredient in detergents. This condition is consistent with findings from previous studies. Laundry wastewater in Pedurungan District, Semarang, Central Java, Indonesia was reported to contain LAS levels ranging from 25 to 33.9 mg·dm^{-3} (Ardiyanto and Yuantari, 2016). The accumulation of LAS surfactants in laundry effluents can lead to multiple adverse effects on aquatic environments. The LAS is known to exhibit toxic characteristics toward aquatic organisms due to its ability to disrupt cell membranes and interfere with respiratory processes in both micro- and macro-organisms (Daulay *et al.*, 2023). Additionally, the presence of LAS increases turbidity, hampers the activity of decomposer microorganisms responsible for biodegradation, and inhibits light penetration required for phytoplankton photosynthesis. Given these circumstances, LAS concentrations exceeding quality standards, as observed in this study, may impose ecological pressure on aquatic systems.

EFFECT OF CHICKEN EGGSHELL AND COCONUT SHELL-BASED ADSORBENTS ON REMOVAL OF LINEAR ALKYLBENZENE SULPHONATE

The application of combined eggshell and coconut shell-based adsorbents resulted in a substantial reduction in LAS concentration in the laundry wastewater. The final LAS levels decreased to 0.76–4.46 mg·dm^{-3}, compared to the pre-treatment concentration of 16.34 mg·dm^{-3}. The most pronounced reduction occurred in sample C120 (50% eggshell carbon:50% coconut shell carbon, 120 min), which yielded the lowest final LAS concentration of 0.76 mg·dm^{-3} (Tab. 3, Fig. 4). In contrast, the lowest reduction was observed in sample A60 (100% eggshell carbon:0% coconut shell carbon, 60 min), which resulted in a final LAS concentration of 4.46 mg·dm^{-3}.

Table 3. Concentration of linear alkylbenzene sulphonate (LAS) in laundry wastewater after adsorbent application

Sample	LAS (mg·dm^{-3})		Mean LAS concentration (mg·dm^{-3})	Standard deviation (*SD*)
	1	2		
A60	4.6	4.31	4.46	0.21
A90	4.11	4.34	4.23	0.16
A120	2.08	2.05	2.07	0.02
A150	2.56	2.72	2.64	0.11
B60	0.93	0.88	0.91	0.04
B90	1.31	1.21	1.26	0.07
B120	1.04	0.98	1.01	0.04
B150	0.77	0.84	0.81	0.05
C60	0.83	0.89	0.86	0.04
C90	0.83	0.70	0.77	0.09
C120	0,70	0.82	0.76	0.08
C150	0.86	1.14	1.00	0.20
D60	1.09	1.12	1.11	0.02
D90	1.31	0.88	1.10	0.30
D120	0.84	0.81	0.83	0.02
D150	0.76	0.78	0.77	0.01
E60	0.92	0.86	0.89	0.04
E90	0.98	0.98	0.98	0.00
E120	0.82	0.75	0.79	0.05
E150	0.92	0.92	0.92	0.00

Explanations: A, B, C, and D as in Tab. 1, the number 60, 90, 120, 150 = the reaction times (min).
Source: own study.

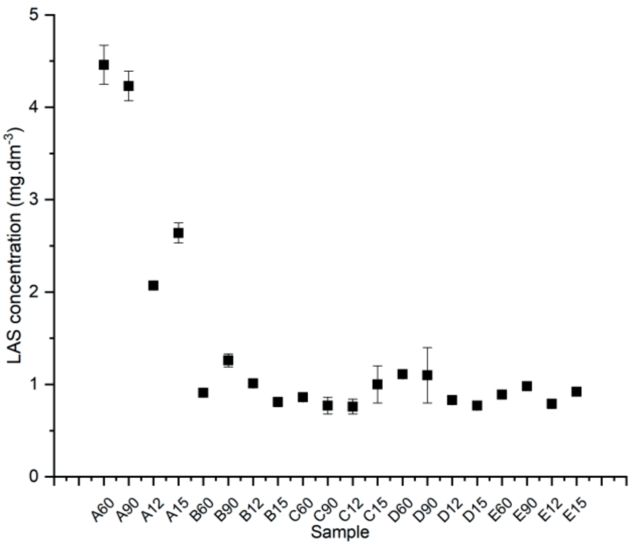

Fig. 4. Concentration of linear alkylbenzene sulphonate (LAS) after adsorbent application; A, B, C, and D as in Tab. 1, the number 60, 90, 120, 150 = the reaction times (min); source: own study

Based on the duplicate measurements of all samples, *SD* values ranged from 0.00 to 0.21 mg·dm^{-3}. This narrow *SD* range indicates low variability between replicates and demonstrates consistent measurement results (Skoog, Holler and Crouch, 2017).

ADSORPTION EFFECTIVENESS OF ADSORBENT

The adsorption effectiveness (*Ef*) was determined based on the amount of LAS removed by the adsorbent. The highest adsorption effectiveness was obtained at the 50:50 composition ratio (sample C) with a contact time of 120 min (95.35%), indicating optimal synergy between the two adsorbent materials. At this ratio, the contribution of coconut shell activated carbon provided a high specific surface area and dominant microporosity essential for physical adsorption of LAS (Masthura and Zulkarnain, 2018), while the chicken eggshell component, rich in calcium carbonate ($CaCO_3$), enhanced adsorption kinetics through electrostatic interactions between Ca^{2+} ions and the sulphonate (SO_3^-) group of LAS (Mustan *et al*., 2020). In contrast, the lowest effectiveness (72.74%) occurred at the 100:0 ratio (sample A) with a 60-minute contact time, demonstrating the limited adsorption capacity of chicken eggshell activated carbon when used alone, especially under short contact duration. This limitation is associated with its lower specific surface area and porosity compared to carbonised coconut shell (Salamah *et al*., 2023).

An evaluation based on the mean adsorption effectiveness of each composition ratio provides a clearer distinction among the tested adsorbents (Tab. 4). The 100:0 ratio (sample A) exhibited a markedly lower average effectiveness (79.52%), confirming that eggshell activated carbon alone was less effective for LAS removal. In contrast, the mixed adsorbent systems showed substantially higher and relatively comparable mean effectiveness values, with averages of 93.91% for the 75:25 ratio (sample B), 94.82% for the 50:50 ratio (C), and 94.20% for the 25:75 ratio (D). Among these, the 50:50 composition achieved the highest mean adsorption effectiveness (94.82%), indicating that this ratio represents the most effective and balanced adsorbent configuration under the studied conditions.

It is also noteworthy that the 0:100 composition ratio (sample E) exhibited a high mean adsorption effectiveness of 94.53%, comparable to that of the mixed adsorbent systems. This behaviour can be attributed to the inherently high specific surface area and well-developed microporous structure of coconut shell–based activated carbon, which strongly supports physical adsorp-

Table 4. Average adsorption efficiency of adsorbents at different composition ratios

Activated carbon composition ratio (egg shell: coconut shell)	Efficiency (%) at contact time (min)				Average efficiency (%)
	60	90	120	150	
100:0 (A)	72.74	74.14	87.36	83.84	79.52
75:25 (B)	94.46	92.29	93.82	95.07	93.91
50:50 (C)	94.74	95.32	95.35	93.88	94.82
25:75 (D)	93.24	93.30	94.95	95.29	94.20
0:100 (E)	94.55	94.00	95.20	94.37	94.53

Source: own study.

tion of organic surfactants such as LAS (Heryanto *et al.*, 2024). The extensive pore network facilitates efficient diffusion and accumulation of LAS molecules within internal adsorption sites, resulting in high removal efficiency even in the absence of additional reactive components (Ramadhani *et al.*, 2020). However, despite its high average effectiveness, the performance of the 0:100 ratio was slightly less balanced than that of the 50:50 composition, indicating that the incorporation of calcium-containing eggshell material contributes to a more stable adsorption system through the combined effects of physical adsorption and electrostatic interactions.

Overall, the relatively narrow spread of adsorption effectiveness values, reflected by an average effectiveness of 93.39% with a low standard deviation (SD = 0.07), indicates that the adsorption process was generally stable across the tested conditions (Skoog, Holler and Crouch, 2017).

At the longest contact time evaluated (150 min), the effectiveness trend slightly shifted (Tab. 4). The 25:75 ratio (sample D) yielded the highest efficiency (95.29%), followed by 75:25 (B – 95.07%) and 50:50 (C – 93.88%), while the lowest value remained at 100:0 (A – 83.84%). This variation is influenced by the physicochemical characteristics of the adsorbents. Coconut shell activated carbon, although highly microporous and having a large surface area, is strongly hydrophobic (Masthura and Zulkarnain, 2018; Xu *et al.*, 2022). Its hydrophobic nature requires a longer wetting period for wastewater to fully penetrate and diffuse into internal pores. At extended contact durations (150 min), its adsorption performance gradually increases as wetting becomes more complete and LAS molecules diffuse more effectively into micropore active sites, consistent with the behaviour of activated carbon requiring sufficient time to reach equilibrium within complex pore networks (Zaini, Arshad and Syed-Hassan, 2023).

The effect of contact time on LAS adsorption efficiency showed a consistent trend across all adsorbent composition ratios. At shorter contact times (60–90 min), adsorption efficiency increased rapidly, indicating that a large number of active sites were still available on the adsorbent surface and that mass transfer from the solution to the adsorbent occurred efficiently. As contact time increased (120 min), the rate of adsorption gradually decreased, suggesting that the adsorption process approached equilibrium as active sites became progressively occupied. Beyond a certain contact time (150 min), further increases did not result in significant improvements in adsorption efficiency, and slight fluctuations were observed for some composition ratios (ratio 25:75 – D and 75:25 – B). This behaviour indicates that the adsorption–desorption processes began to balance, particularly under prolonged contact conditions. Similar trends have been commonly reported for surfactant adsorption onto carbon-based adsorbents, where extended contact times do not necessarily enhance removal efficiency once equilibrium is reached (Lima and Oliveira de, 2025). Therefore, contact time plays a critical role in determining adsorption performance, and excessively long contact durations may not be practically advantageous for small-scale laundry wastewater treatment applications.

ADSORPTION CAPACITY OF ADSORBENT

The highest adsorption capacity was achieved at the 50:50 composition ratio (sample C) with a contact time of 120 min, reaching 0.15580 mg·g^{-1} (rounded to 0.156 mg·g^{-1}) – Figure 5.

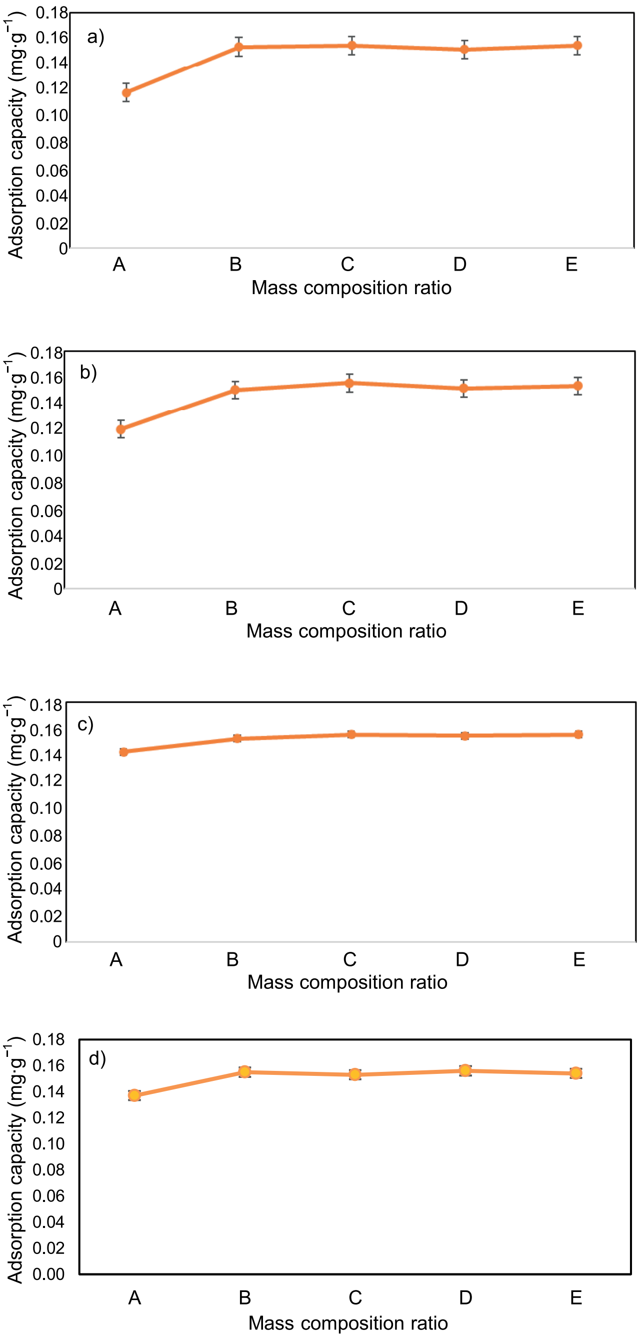

Fig. 5. Adsorption capacity of linear alkylbenzene sulphonate (LAS) for different adsorbent composition ratios at contact time of: a) 60 min, b) 90 min, c) 120 min, d) 150 min; A, B, C, D, and E as in Tab. 1; source: own study

This value indicates that each gram of the mixed adsorbent was able to bind 0.156 mg of LAS. It should be noted that the adsorption capacity (q_e) reported herein represents the sorption performance under specific operating conditions (initial LAS concentration, contact time, adsorbent dosage, and ambient temperature) and should not be interpreted as the maximum adsorption capacity (q_{max}), which is typically obtained through adsorption isotherm modelling. The superior capacity at the 50:50 ratio suggests that the combination of chicken eggshell and coconut shell–based adsorbent provides a more optimal number of active sites, resulting in a more effective adsorption process. This finding aligns with the adsorption effectiveness results, which also identified this ratio as the best-performing treatment, confirming the synergistic interaction of both materials (equilibrium condition) (Subhan *et al.*, 2022). In contrast, the lowest adsorption capacity was recorded at the 100:0 ratio (sample A) with a 60-minute contact time, yielding 0.11885 mg·g^{-1} (approximately 0.119 mg·g^{-1}). This indicates that eggshell activated carbon alone has a lower adsorption capability than the combined adsorbent or coconut shell activated carbon. This limitation is attributed to the lower porosity and smaller surface area of eggshell carbon compared to coconut-shell carbon, reducing the amount of LAS that can be adsorbed per gram of material (Pardede, 2020).

When compared with other adsorbents reported for LAS and anionic surfactant removal, the adsorption capacities obtained in this study fall within the lower range typically observed for low-cost waste-derived carbon materials evaluated under non-optimised and application-oriented conditions. Studies on biochar and other waste-derived carbons have shown that adsorption capacity is strongly influenced by feedstock characteristics, surface functional groups, and experimental conditions, and relatively modest capacities are commonly reported when intensive activation or surface modification is not employed (Bautista Quispe *et al.*, 2024). Accordingly, the adsorption capacities reported in this study should be interpreted as material performance under realistic laboratory-scale conditions rather than as indicators of maximum adsorption potential.

At the longest contact time of 150 min, the adsorption capacities showed fluctuations, indicating that desorption began to occur alongside adsorption. Under these conditions, the adsorption capacity of the 100:0 (A) and 50:50 (C) ratios slightly decreased to 0.137 mg·g^{-1} and 0.153 mg·g^{-1}. In contrast, the 25:75 (D – 0.156 mg·g^{-1}) and 75:25 (B – 0.155 mg·g^{-1}) ratios remained high or increased. This behaviour indicates continued intraparticle diffusion at longer contact times, enabling LAS molecules to access deeper pores, particularly in fine-pore coconut shell carbon (25:75) or at exposed Ca^{2+} reactive sites (75:25) (Ruhmawati, Budiasyah, T. and Setiawan, 2020). Because all experiments were conducted under controlled laboratory conditions at ambient temperature, the observed adsorption capacities represent sorption performance under typical room-temperature conditions commonly encountered in small-scale laundry operations. Variations in process temperature could influence adsorption behaviour by affecting surfactant diffusion, solubility, and adsorbent–adsorbate interactions; therefore, further studies are required to evaluate temperature-dependent adsorption mechanisms and long-term performance.

Based on all indicators, final LAS concentration, removal effectiveness (*Ef*), and adsorption capacity (q_e), the most effective treatment was the 50% chicken eggshell activated carbon:50% coconut-shell activated carbon ratio with a 120-min contact time. At this condition, LAS levels were reduced to 0.77 mg·g^{-1}, representing the largest removal across all tests and far below the quality standard of 3.00 mg·g^{-1} (Central Java, Indonesia regulatory). The 95.32% effectiveness and 0.156 mg·g^{-1} adsorption capacity indicate that this combination achieved the best overall performance within the experimental range in this study.

In comparation with previously reported adsorbents, the combined use of chicken eggshell and coconut shell-based activated carbon in this study exhibited relatively higher LAS removal efficiency under the investigated conditions. For example, Fasihah, Maryani and Heriyanto (2022) reported a LAS removal efficiency of 38.85% using eggshell alone, while Nulloh, Supriatna and Amalia (2023) achieved 45.69% using corn-cob derived activated carbon. In another study, a combination of eggshell and zeolite at an optimal mass ratio of 0.7:0.3 g resulted in an adsorption capacity of 0.6553 mg·g^{-1} with an adsorption efficiency of 25.21%, indicating a lower reported adsorption performance under the applied experimental conditions (Listianti and Sutanto, 2024). Other studies employing different adsorbent combinations have demonstrated high adsorption efficiencies for different pollutants, such as dyes; however, direct comparison with LAS removal is limited due to differences in contaminant characteristics. Nevertheless, these findings indicate that synergistic combinations of bio-based adsorbents can enhance adsorption performance.

Beyond adsorption performance, the result of this study also highlight the practical potential of combining carbonised chicken eggshell and coconut shell as bio-based adsorbents for laundry wastewater treatment, particularly at household and small-scale commercial levels. From an economic perspective, chicken eggshells and coconut shell are quite abundant, especially in tropical countries (Basnett *et al.*, 2019). These materials are low-cost waste materials, and their utilisation may reduce raw material costs compared to commercial activated carbon while simultaneously supporting sustainable waste management practices (Buksh *et al.*, 2018). Furthermore, the relatively simple preparation process and adsorption mechanism indicate that the tested adsorbent compositions could be further developed as pre-treatment media or column-based filtration system for small-scale laundry operations. Nevertheless, a detailed techno-economic assessment is still required to comprehensively evaluate long-term feasibility, operational costs, and overall cost-effectiveness.

CONCLUSIONS

This study indicated that the combined chicken eggshell and coconut shell-based adsorbents was highly effective in reducing LAS concentrations in laundry wastewater, achieving a removal efficiency of 95.35% and an adsorption capacity of 0.156 mg·g^{-1}. Thereby highlighting its strong potential as a sustainable surfactant removal medium. Moreover, the best variation that achieved the highest reduction of LAS in laundry wastewater (200 cm^3) was the 50%:50% ratio of carbonised chicken eggshell to coconut-shell from a total of 20 grams of adsorbent, with a contact time of 120 min.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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