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Research Article

Biodegradation of sodium lauryl ether sulfate (SLES) contamination by *Pseudomonas aeruginosa* isolates

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Abstract

Sodium lauryl ether sulfate (SLES) is a surfactant commonly used in the formulation of detergents, which is typically disposed of in wastewater treatment plants. The current study describes the effectiveness of bacteria isolated from Iraqi wastewater to remove SLES. 16S rRNA genetic analysis revealed that this strain is *Pseudomonas aeruginosa*. Three temperatures (30, 35, and 40°C) and pH values (5,7, and 9) were chosen for this study, and three concentrations of SLES (25, 50, and 100 mg/L) were used. The SLES anionic surfactant showed that the best biodegradation by *Pseudomonas aeruginosa* was at a temperature of 30°C and both pH 7 and 9, while the removal percentages for them were 98.44% and 96.36%, respectively, at 25 mg/L of SLES. The outcomes of this study revealed the potential and significance of SLES removal in actual effluents by aerobic biodegradation. The ability of this bacterium to degrade SLES makes the bacterium an important tool for bioremediation.

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Introduction

Sixty percent of surfactants produced globally are anionic, and sodium lauryl ether sulfate (SLES) is one of the widely anionic surfactants used, which is a blend of primary linear alkyl ether sulfates (AES) (Holmberg et al., 2002; Al-Ani et al., 2019). The molecular formula for SLES is ($CH_3[CH_2]_{11}[OCH_2CH_2]n\ OSO_3Na^+$), which is the most frequently utilized for household and industrial applications. It is used in many products, including detergents, cosmetics, and items for personal care, due to its inexpensive production and strong emulsifying and foaming qualities (Caracciolo et al., 2017).

Surfactants are widely used, and as a result, they frequently exist in industrial and household wastewater. According to reports, the majority of surfactants are biodegradable to some extent because surfactants have complex structures and high molecular weights, and the biodegradation pathways frequently involve multiple steps (Jimenez et al., 1991; van Ginkel, 1996; Al-Shamma and Hassan, 2018). According to Bennie (1999) and Itrich and Federle (2004), the biodegradation of metabolites generated through surfactant biodegradation could be slower than that of the parent substance. In streams and rivers near dams or obstructions, large masses of foam have been developed as a result of incomplete surfactant biodegradation (Jakobi and Lchr, 1987).

Wastewater is treated using a range of methods, including chemical, biological, and physical treatment, to remove surfactants. The best method for treating wastewater will depend on a number of factors, including energy consumption, treatment costs, environmental impact, influent and effluent quality, and treatment costs (Jamaly et al., 2015). Physical treatment techniques have the advantages of being robust, chemical-free, and requiring less operational input; on the other hand, their main disadvantages are producing secondary waste, having a high capital cost (requiring land/space), and having a long retention period (Fakhru'l-Razi et al., 2009).

Chemical methods have advantages, such as reduced sludge generation and high pollutant removal

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efficiency, but they also have drawbacks, such as high operational and chemical costs and secondary waste production (Jain et al., 2017). Biological methods have the advantages of low cost and easy application (Shannon et al., 2008). The study of the decomposition of anionic surfactants by microorganisms is considered very important in reducing their environmental impact. Bacterial activity is the main reason responsible for the degradation of surfactants in the ecosystem. In addition to improving the removal of these surfactants from the environment and reducing their impact on ecosystems, biodegradation is an essential process for treating surfactants found in raw sewage in treatment plants. Microbes can co-metabolize surfactants through microbial metabolic reactions or use them as substrates for energy and nutrients during biodegradation (Qiao et al., 2020).

Some recent studies have indicated that SLES can be broken down by the bacterial consortia that were isolated from wastewater and activated sludge. Most of the consortia's identified bacteria were members of the Gammaproteobacteria family, which includes *Aeromonas*, *Serratia*, *Pseudomonas*, *Alcaligenes*, *Azotobacter*, *Enterobacter*, *Klebsiella,* and *Acinetobacter* (Khleifat, 2006; Paulo et al., 2017; Najim et al., 2022). According to Budnik et al. (2016), ether cleavage is the primary method of aerobic degradation of SLES. This process produces intermediate compounds that can undergo additional degradation and release sulfate. A further potential mechanism involves the direct cleavage of the AES ester to split the sulfate, which occurs prior to the carbon body's degradation (Hales et al., 1986).

This study aimed to isolate and assess the efficiency of an aerobic bacterial strain that can degrade SLES.

Materials and Methods

Chemicals and media

SLES and other biochemicals were purchased from Sigma (USA), and acetone was used to dissolve SLES and create a stock of 1,000 mg/L. To be used, the stock solution was filter-sterilized and stored in the refrigerator. The bacterial strains that degraded SLES were isolated and cultivated using nutrient broth, nutrient agar, and mineral salt media, as stated by Singh et al. (2007). The composition of mineral salt medium (MSM) was prepared according to Miller (1972).

Isolation and screening of bacteria that degrade SLES

Samples were taken from three sewage treatment plants that were contaminated with surfactant (in December 2022), which have been given numbers (1, 2, and 3) belonging to Al-Kut City, which is located in the Wasit Governorate/Iraq. For enrichment, sewage samples (10 mL) were added to 250 mL Erlenmeyer flasks containing 150 mL MSM supplemented with 50 mg/L SLES for enrichment. The flasks were then incubated for five days at 150 rpm and 30ºC (Asok and Jisha, 2012). The pour plate method was used for the isolation of bacteria using nutrient agar from the last enrichment culture, according to Andrew et al. (2002).

Bacterial cultures that SLES degrading were selected by:

1. Primary screening is carried out by cultivating them on nutrient agar plates with 200 mg/L of SLES as the only source of energy and carbon, as stated by Ghose et al. (2009).
2. Secondary screening was carried out via cultivation on solid (MSM) that were incubated at 30ºC for 24 to 96 hours, with SLES serving as the only source of energy and carbon at concentrations between 200 to 2,000 mg/L. The growth of bacterial isolates was based on the bacteria's growth on solid mineral salt media (Singh et al., 2007; AlMamoory and Al-Mayaly, 2017).

Identification of the bacterial strain that degrades SLES

In addition to studying the shape, color, odor, and margin of the colonies grown on nutrient agar, microscopic analysis of slides stained with gram stain was conducted to distinguish gram-negative and/or gram-positive bacteria (Harley, 2016). The isolated bacteria were diagnosed by PCR technology, and amplification was done using forward primer 5`- AGA GTT TGA TCM TGG CTC AG - 3` and reverse primer 5`-TAC GGY TAC CTT GTT ACG ACT T -3`. Molecular evolutionary analyses of SLES degrading bacteria based on 16S r-RNA genes were conducted using MEGA version 4 (Tamura et al., 2007).

Laboratory experiment

Sets of 250 mL Erlenmeyer flasks holding 100 mL of the medium were prepared, the pH was adjusted to 7 and autoclaved at 121ºC and 1.5 bar for 15 min, then sets of SLES with three concentrations (25, 50, and 100 mg/L) added to flasks, then added inoculum of Pseudomonas. aeruginosa that was isolated and incubated after being activated in nutrient broth overnight, the flasks were incubated in a shaker incubator (150 rpm) for 15 days, and the growth was measured by recorded values of optical density by spectrophotometer each two days (Abboud et al., 2007). The experiment was repeated for pH 5 and 9 at three different temperature degrees (30, 35, and 40°C) for 15 days, optical density was measured for each one, then 5 mL of the mixture was taken to test the biodegradation efficacy by HPLC analysis.

High-Performance Liquid Chromatography (HPLC)

The concentrations used in the current study were 25, 50, and 100 mg/L, which were measured according to Equation 1.

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$C1 \times V\mathbf{1} = C\mathbf{2} \times C\mathbf{2}$ (1)

HPLC was used to determine the SLES content, and the following equations were used to calculate the percentage of SLES biodegradation (Equations 2 and 3) (Shu and Ding, 2005):

$$\text{Percentage of biodegradation} = \frac{\text{conc.of standard} - \text{conc.of sample}}{\text{conc.of standard}} \text{ X } 100 \quad (2)$$

or

$$\text{Percentage of biodegradation} = \frac{\text{beak area of standard} - \text{beak area of sample}}{\text{beak area of standard}} \text{ X } 100 \quad (3)$$

Results and discussion

Identification of bacteria

In this study, sewage samples from one of the wastewater plants in Wasit province, Iraq, were considered a significant source of locally prevalent bacteria that can mineralize anionic surfactants. The SLES-degrading strain isolated in this study were gram-negative rods. *Pseudomonas aeruginosa*, were isolated, purified, and selected based and selected based due to their capability to use SLES as a source of carbon. The bacterial isolate *P. aeruginosa* was identified based on the nucleotide sequence of the 16S rRNA gene (PCR technology).

Impact of temperature and pH on the growth of Pseudomonas aeruginosa

Surfactant biological degradation is typically influenced by a number of factors. It is well known that the rate of degradation is affected by environmental factors such as temperature, pH, shaking, and nutrient availability (Abou-Zeid et al., 2001). The current study examined the effects of temperature and pH on SLES degradation. The results presented in Table 1 demonstrate that notable differences exist in the growth of bacteria at various temperatures and pH levels. The best and most significant means of bacterial growth under 30, 35, and 40ºC recorded at pH 7 were 0.410, 0.366, and 0.110 nm, respectively. Also, the better and more significant means of bacterial growth under pH (5, 7, and 9) measured at 30ºC were 0.360, 0.410, and 0.370 nm, respectively. The mean value of *P. aerogenosa* growth was highest at 30ºC and pH 7, which was 0.410 nm, and lowest at 40ºC and pH 5, which was 0.081 nm (Figures 1 and 2). Accordingly, the optimal degradation occurs at a temperature of 30ºC for isolated bacteria.

Table 1. The mean value of *P. aeruginosa* growth at various temperatures and pH degrees after incubation for 15 days and the LSD value was 25 mg/L of SLES.

Temperatures	**pH**			
	pH 5	**pH 7**	**pH 9**	**LSD value**
30ºC	0.360 ±0.085	0.410 ±0.157	0.370 ±0.165	0.220 NS
35ºC	0.205 ±0.126	0.366 ±0.121	0.282 ±0.114	0.122*
40ºC	0.081 ±0.021	0.110 ±0.024	0.091 ±0.028	0.053 NS
LSD value	0.086*	0.119 *	0.138 *	---

*($p \leq 0.05$), NS: non-significant.

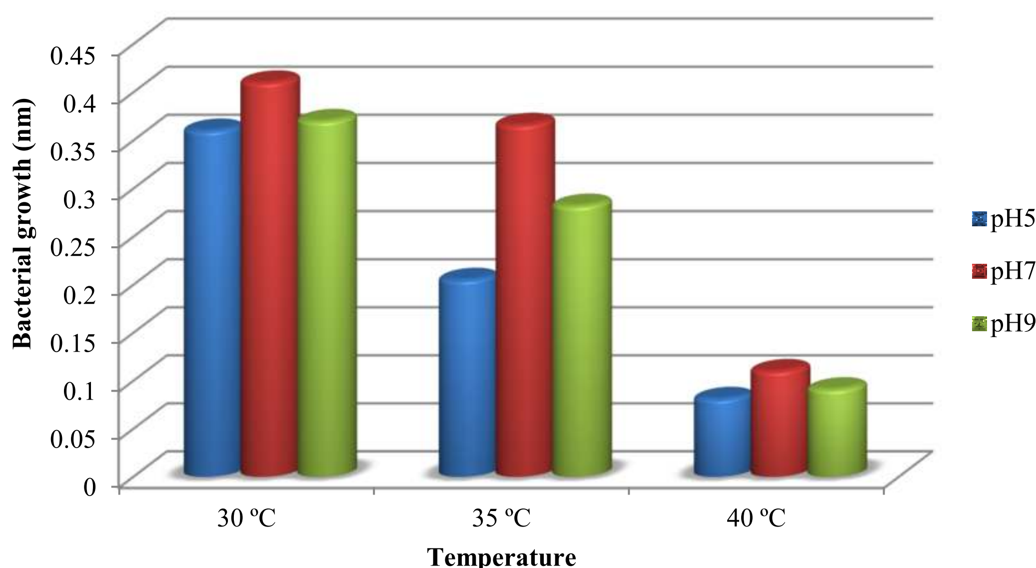

Figure 1. Mean value of *P. aeruginosa* growth at various temperatures and pH values after incubation for 15 days.

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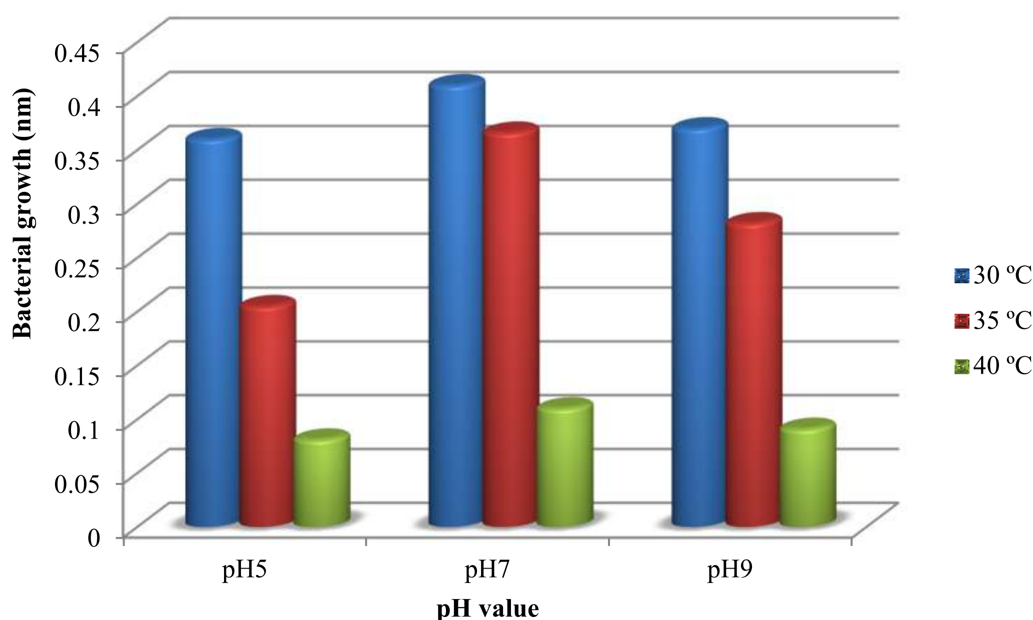

Figure 2. Mean value of *P. aeruginosa* growth at various pH values and temperatures after incubation for 15 days.

Similar research revealed that 30°C was necessary for the optimal degradation of surfactants by *Citrobacter braakii*, *Pseudomonas*, *Delftia acidovorans*, *Acinetobacter calcoaceticus*, and *Pantoea agglomerans* (Schulz et al., 2000: Dhouib et al., 2003; Khleifat, 2006; Abboud et al., 2007). Temperature and microbial activity were found to be directly correlated during SLES degradation. In addition to potentially affecting growth, a temperature increase above the threshold point of 37ºC may also make microbial membranes more toxic. According to the data, 30ºC would be the ideal temperature for better SLES degradation, as confirmed by HPLC. In general, temperature influences the SLES compound's chemical and physical characteristics, microbial metabolism, the specific growth average of microorganisms, the rate of the oxidation process's enzymatic activity, and the makeup of the microbial community, all of which have an impact on the SLES biodegradation rate (Abboud et al., 2007).

The degradative activity of bacteria is significantly influenced by pH (Wong et al., 2002). The results indicated that the ideal pH for *P. aeruginosa* growth in MSM containing SLES is 7; this conclusion is corroborated by the findings of Amirmozafari et al. (2007), who found that isolated strains of Pseudomonas can grow and maintain their capacity for degradation across a broad pH range, with optimal growth occurring at pH roughly. Dhouib et al. (2003) reported that many SLES-degrading bacteria, including *Citrobacter braakii*, grow optimally on SLES at a pH of 7. The pH level may have an impact on the enzyme(s) responsible for SLES degradation (Prats et al., 2006).

Impact of incubation time on biodegradation and growth

Table 2 displays the results, which show a significant difference ($p<0.05$) between the bacterial growth means for various incubation times. After the fifteenth day of incubation, the selected bacteria isolated showed that the highest mean growth was on the ninth day (0.540 nm), and the lowest growth was on the first day (0.230 nm). The growth rate of the selected bacteria that were isolated increased gradually from one day to the ninth day and then started to decrease (Figure 3).

Table 2. Average values ± standard deviation of bacterial growth at 600 nm at various incubation times and LSD value.

Incubation period Days	Mean± SD of bacterial growth *P. aerogenosa*
First Day	0.230 ± 0.015
Third Day	0.370 ± 0.012
Fifth Day	0.420 ± 0.012
Seventh Day	0.495 ± 0.010
Ninth Day	0.540 ± 0.015
Eleventh Day	0.465 ± 0.010
Thirteenth Day	0.410 ± 0.021
Fifteenth Day	0.350 ± 0.031
LSD ≤ 0.05	0.029

SLES degradation significantly increased as the incubation times increased. According to Hosseini et al. (2007), after 120 hours, *Pseudomonas beteli* was able to degrade 94% of the SDS levels. It is commonly

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known that extending the incubation period increases the number of viable organisms, especially on medium with minimal amounts of nutrients, and as a result of contaminant concentration depletion and the production of intermediate substances and metabolic byproducts, which causes a lower media pH and subsequently inhibit bacterial growth (Naveenkumar et al., 2010).

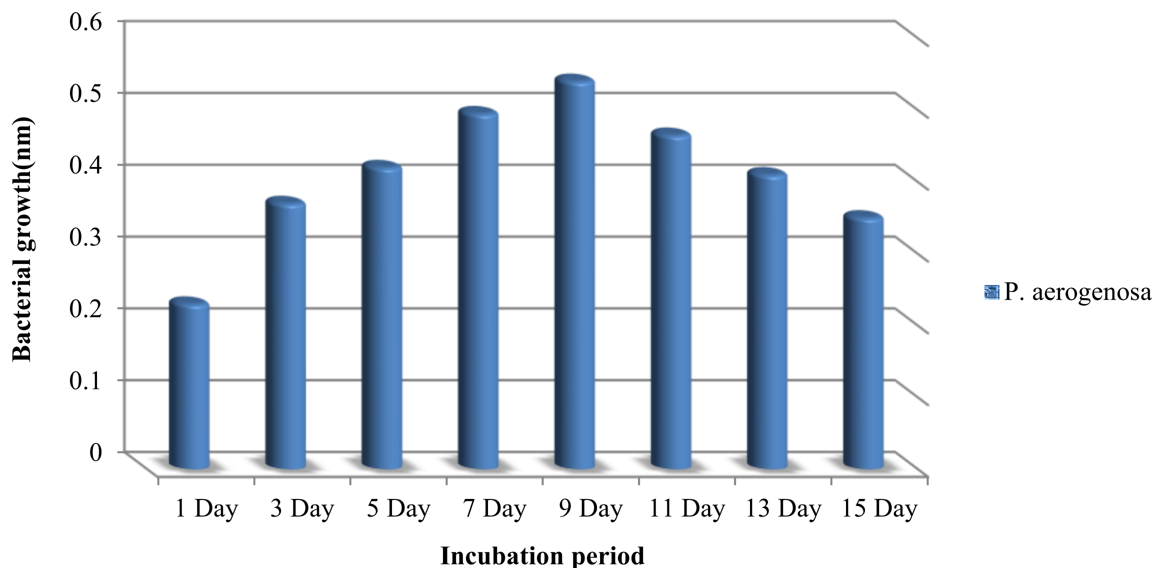
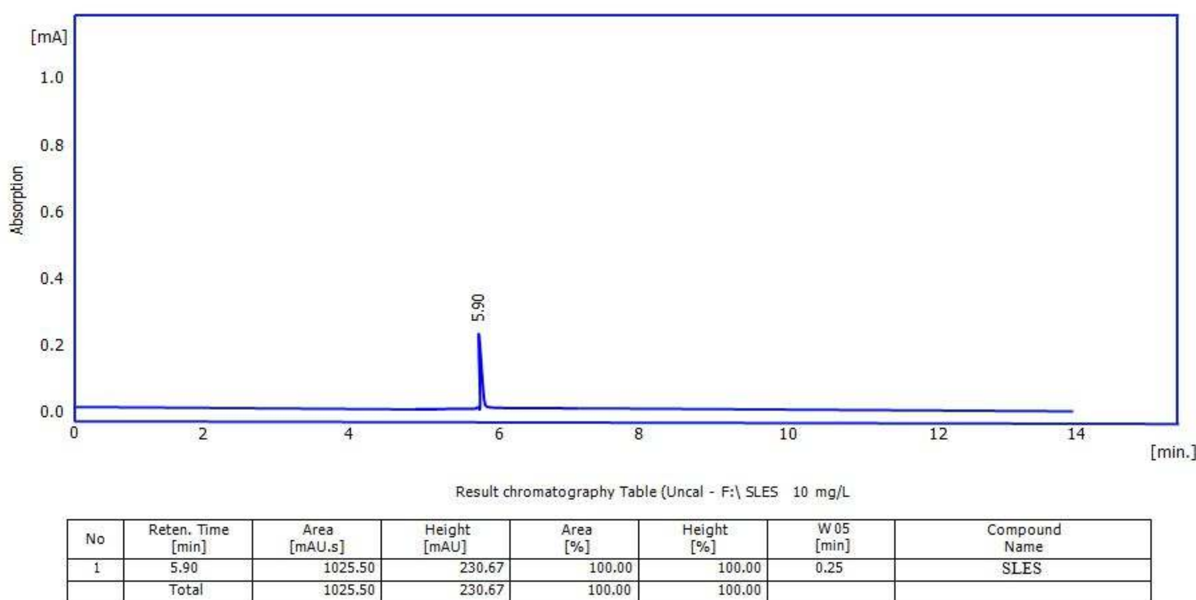


Figure 3. The average value of bacterial growth over various incubation times.

HPLC analysis of biodegraded SLES

For the degradation efficacy test, the bacteria were inoculated into a mineral salt medium, with SLES at three concentrations (25, 50, and 100 mg/L); the surfactant was added to 100 mL of mineral salts medium at three different temperature degrees and pH. These samples were analyzed with HPLC system (Fedeila et al., 2018). An analysis of a standard solution of surfactant was done, where the concentration of the standard solution was 10 mg/L, and the beak area was (1,025.5) per (5.90) minute. The comparing figures of SLES were done according to the concentrations used in the study (Figure 4). The results of the HPLC analysis are mentioned in Table 3, which explains the concentrations of SLES, beak area of samples, percentage of removal, and remaining concentration for each sample.



Result chromatography Table (Uncal - F:\ SLES 10 mg/L

No	Reten. Time [min]	Area [mAU.s]	Height [mAU]	Area [%]	Height [%]	W 05 [min]	Compound Name
1	5.90	1025.50	230.67	100.00	100.00	0.25	SLES
	Total	1025.50	230.67	100.00	100.00		

Figure 4. Beak area for 10 mg/L of SLES.

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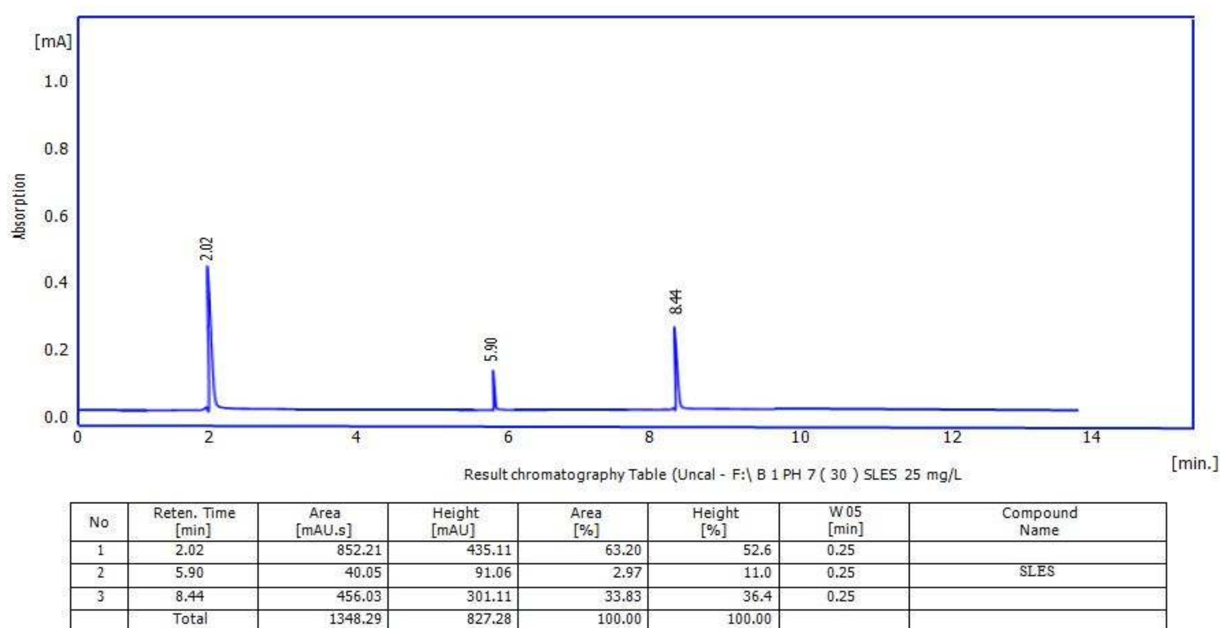
Table 3. Beak area and removal percent of samples.

Temperature (◦C)	Concentration of SLES (mg/L)	pH	Beak area (mAU.s)	% removal	Remaining concentration (mg/L)
30	25	9	93.27	96.36	0.91
		7	40.05	98.44	0.39
		5	205.61	91.98	2.005
	50	9	763.48	85.1	7.45
		7	460.95	91	4.5
		5	1,384.01	73	13.5
	100	9	2,947.06	71.26	28.74
		7	2,152.33	79	21
		5	3,691.22	64	36
35	25	9	332.25	87.04	3.24
		7	230.52	91	2.25
		5	509.85	80	5
	50	9	1,281.45	75	12.5
		7	871.57	83	8.5
		5	1,583.06	69.12	15.44
	100	9	3,794.05	63	37
		7	2,661.99	74.04	25.96
		5	5,112.05	50.15	49.85
40	25	9	2,075.12	19.08	20.23
		7	2,047.18	20.15	19.96
		5	2,127.58	17	20.75
	50	9	4,296.81	16.2	41.9
		7	4,186.05	18.36	40.82
		5	4,409.55	14	43
	100	9	8,818.75	14	86
		7	8,603.46	16.1	83.9
		5	9,023.46	12	88

In Table 3, the dissociation of SLES surfactant in different concentrations with different temperatures and pH, where the best result was the dissolution of the SLES into its secondary components at a temperature of 30ºC and pH 7 (Figure 5) with the concentration used 25 mg/L, and the lowest results were at temperature 40ºC at pH 5 with the concentration used 100 mg/L as in (Figure 6).



No	Reten. Time [min]	Area [mAU.s]	Height [mAU]	Area [%]	Height [%]	W 05 [min]	Compound Name
1	2.02	852.21	435.11	63.20	52.6	0.25	
2	5.90	40.05	91.06	2.97	11.0	0.25	SLES
3	8.44	456.03	301.11	33.83	36.4	0.25	
	Total	1348.29	827.28	100.00	100.00		

Figure 5. The highest removal of SLES.

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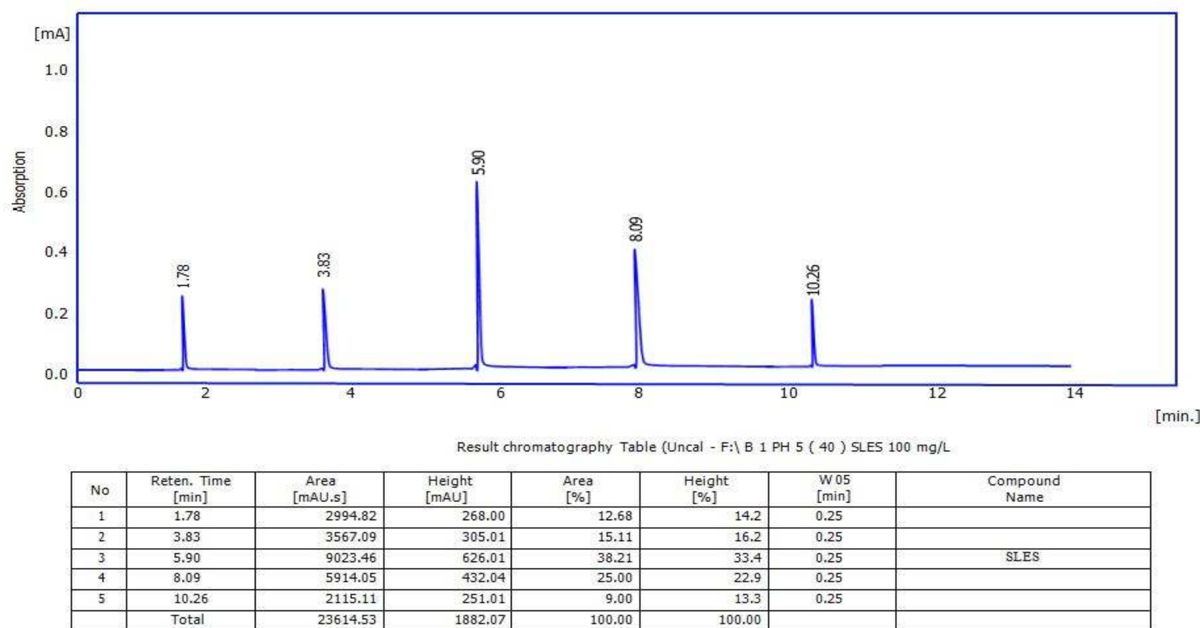

No	Reten. Time [min]	Area [mAU.s]	Height [mAU]	Area [%]	Height [%]	W 05 [min]	Compound Name
1	1.78	2994.82	268.00	12.68	14.2	0.25	
2	3.83	3567.09	305.01	15.11	16.2	0.25	
3	5.90	9023.46	626.01	38.21	33.4	0.25	SLES
4	8.09	5914.05	432.04	25.00	22.9	0.25	
5	10.26	2115.11	251.01	9.00	13.3	0.25	
	Total	23614.53	1882.07	100.00	100.00		

Figure 6. The lowest removal of SLES.

This means that the higher the concentration of SLES and the lower the pH value, the less efficient this bacterium is in degrading the surfactant. The degradation percentage increased with 25 mg/L of SLES and reduced at 100 mg/L, Fedeila et al. (2018), which shows more efficiency degrading at a neutral degree of pH; however, at acidic pH, with nearly 50% degrading rate, while at alkaline pH gave nearly 80% degrading rate at different concentrations and amounts of surfactant. Also, Asok and Jisha (2012) showed that neutral environments cause more degradation than alkaline and acidic environments because in acidic environments, the stability of bonds increases. Numerous bacterial strains that are able to break down comparable substances have been isolated from environments contaminated with surfactants (Peressutti et al., 2008).

In this study, high levels of degradation were attained with low concentrations of SLES. The percentage of SLES degradation of *P. aeruginosa* at a concentration of 25 mg/l was 98.44%, while it was 91% and 79 % for concentrations of 50 and 100 mg/L, respectively. Higher concentrations resulted in a noticeable slowdown in the rate of degradation, which appears to be related to the surfactant's harmful effect on bacterial growth (Yadav et al., 2001).

SLES can be poisonous and harmful to microorganisms at certain concentrations. This is due to the SLES adsorption, causing the cell membrane of microorganisms to depolarize, which reduces the absorption of supplements and alters the release of material from cell metabolism. When the concentration of SLES is high, it is deadly to the bacteria because it removes the lipopolysaccharide outer layer of gram-negative bacteria. The microorganisms' viability will eventually decline (Odahara, 2004; Abboud et al., 2007). The *P. aeruginosa* bacteria were able to degrade SLES with good efficiency, indicating that this bacterium presents a good option for SLES disposal from these contaminated environments.

The results agreed with Dhouib et al. (2003), Khleifat (2006), Chaturvedi and Kumar (2010), and Anaukwu et al. (2016), which used bacteria to degrade SLES and showed 75-100% percentage of degradation to SLES explained by HPLC analysis. The slight difference in the percentage of biodigestion is due to the efficiency of the type of bacteria, the isolated strain type, and its adaptation to the environment (Ran et al., 2016).

Conclusion

In this study, SLES biodegradation at aerobic conditions using isolated microbial cells was investigated from wastewater plants. A SLES-degrading bacterium was isolated from an Iraqi water sample that was contaminated with SLES. In order to promote a higher degradation rate and enable the application of the optimized parameters in the field, growth optimization studies involving the isolate were conducted on a variety of physicochemical parameters. *Pseudomonas aeurginosa*, which has a strong SLES degradation ability, was isolated, purified, and selected based on its capability to use SLES as a source of carbon and enrich it from sewage. The bacterial isolate was identified based on the nucleotide sequence of the 16S rRNA gene (PCR technology). The strain's growth characteristics demonstrated that it could degrade more than 80% of SLES at concentrations less than 100 mg/L. The optimal values of temperature and pH for biodegradation were 30°C and pH 7.

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References

Abboud, M.M., Khleifat, K.M., Batarseh, M., Tarawneh, K.A., Al-Mustafa, A. and Al-Madadhah, M. 2007. Different optimization conditions required for enhancing the biodegradation of linear alkylbenzosulfonate and sodium dodecyl. *Technology* 41:432-439, doi:10.1016/j.enzmictec.2007.03.011.

Abou-Zeid, D.M., Muller, R. and Deckwer, W.D. 2001. Degradation of natural and synthetic polyesters under anaerobic conditions. *Journal of Biotechnology* 86(2):113-26, doi:10.1016/s0168-1656(00)00406-5.

Al-Ani, R.R., Hassan, F.M. and Al-Obaidy, A.M.J. 2019. Quantity and quality of surfactants in sediment of Tigris River, Baghdad, Iraq. *Desalination and Water Treatment* 170:168-175, doi:10.5004/dwt.2019.24679.

AlMamoory, M.H. and Al-Mayaly, I.K. 2017. Biodegradation of cypermethrin by two isolates of *Pseudomonas aeruginosa*. *Iraqi Journal of Science* 58(4C):2309-2321.

Al-Shamma, A. and Hassan, R.A. 2018. Pollution assessment of surface and drainage water by heavy elements in Al Ahrar District, Wasit Governorate, Iraq. *Iraqi Journal of Sciences* 59(2B):886-891.

Amirmozafari, N., Malekzadeh, F., Hosseini, F. and Ghaemi, N. 2007. Isolation and identification of anionic surfactant degrading bacteria from activated sludge. *Iranian Biomedical Journal* 11(2):81-86.

Anaukwu, C.G., Ekwealor, A.I., Ezemba, C.C., Anakwenze, V.N., Agu, K.C., Nwankwegu, A.S., Okeke, B.C. and Awah, N.S. 2016. Influence of anionic, cationic and non-ionic surfactants on growth of hydrocarbon utilizing bacteria. *American Journal of Current Microbiology* 4:10-16.

Andrew, E.J., Hales, S.G., Ur-Rehman, N.G.A. and White, G.F. 2002. Novel alkyl sulphatase required for the biodegradation of the branched primary alkyl sulphate surfactant 2-butyloctyl sulphate. *Applied and Environmental Microbiology* 68:31-36, doi:10.1128/AEM.68.1.31-36.2002.

Asok, A.K. and Jisha, M.S. 2012. Biodegradation of the anionic surfactant linear alkyl benzene sulfonate (LAS) by Autochthonous *Pseudomonas* sp. *Water, Air and Soil Pollution* 223(8):5039-5048, doi:10.1007/s11270-012-1256-8.

Bennie, D.T. 1999. Review of the environmental occurrence of alkylphenols and alkylphenol ethoxylates. *Water Quality Research Journal of Canada* 34(1):79-122, doi.org/10.2166/wqrj.1999.004.

Budnik, I., Zembrzuska, J. and Lukaszewski, Z. 2016. Bacterial strains isolated from river water having the ability to split alcohol ethoxylates by central fission. *Environmental Science and Pollution Research International* 23(14):14231-4239, doi:10.1007/s11356-016-6566-8.

Caracciolo, A.B., Cardoni, M., Pescatore, T. and Patrolecco, L. 2017. Characteristics and environmental fate of the anionic surfactant sodium lauryl ether sulphate (SLES) used as the main component in foaming agents for mechanized tunnelling. *Environmental Pollution* 226:94-103, doi:10.1016/j.envpol.2017.04.008.

Chaturvedi, V. and Kumar, A. 2011. Isolation of a strain of *Pseudomonas putida* capable of metabolizing anionic detergent sodium dodecyl sulfate (SDS). *Iranian Journal of Microbiology* 3:47-53.

Dhouib, A., Hamad, N., Hassari, I. and Sayadi, S. 2003. Degradation of anionic surfactants by *Citrobacter braakii*. *Process Biochemistry* 38(8):1245-1250, doi:10.1016/S0032-9592(02)00322-9.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C., Biak, D.R.A., Madaeni, S.S. and Abidin, Z.Z. 2009. Review of technologies for oil and gas produced water treatment. *Journal of Hazardous Materials* 170:530-551, doi:10.1016/j.jhazmat.2009.05.044.

Fedeila, M., Hachaïchi-Sadouk, Z., Bautista, L.F., Simarro, R. and Nateche, F. 2018. Biodegradation of anionic surfactants by *Alcaligenes faecalis*, *Enterobacter cloacae* and *Serratia marcescens* strains isolated from industrial wastewater. *Ecotoxicology and Environmental Safety* 163:629-635, doi.org/10.1016/j.ecoenv. 2018.07.123.

Ghose, N.C., Saha, D. and Gupta, A. 2009. Synthetic detergents (surfactants) and organochlorine pesticide signatures in surface water and groundwater of Greater Kolkata, India. *Journal of Water Resource and Protection* 4:290-298, doi:10.4236/jwarp.2009.14036.

Hales, S.G., Watson, G.K., Dodgson, K.S. and White, G.F. 1986. A comparative study of the biodegradation of the surfactant sodium dodecyltriethoxy sulphate by four detergent-degrading bacteria. *Journal of General Microbiology* 132(4):953-961, doi:10.1099/00221287-132-4-953.

Harley, J.P. 2016. *Laboratory Exercises in Microbiology*, 10th ed. McGraw Hill Higher Education. New York.

Holmberg, K., Jonsson, B., Kronberg, B. and Lindman, B. 2002. *Surfactants and Polymers in Aqueous Solution*, 2nd ed. Wiley, Chichester, West Sussex.

Hosseini, F., Malekzadeh, F., Amirmozafari, N. and Ghaemi, N. 2007. Biodegradation of anionic surfactants by isolated bacteria from activated sludge. *International Journal of Environmental Science and Technology* 4:127-132, doi:10.1007/BF03325970.

Itrich, N.R. and Federle, T.W. 2004. Effect of ethoxylate number and alkyl chain length on the pathway and kinetics of linear alcohol ethoxylate biodegradation in activated sludge. *Environmental Toxicology and Chemistry* 23(12):2790-2798, doi:10.1897/04-053.1.

Jain, P., Sharma, M., Dureja, P., Sarma, P.M. and Lal, B. 2017. Bioelectrochemical approaches for removal of sulfate, hydrocarbon and salinity from produced water. *Chemosphere* 166:96-108, doi:10.1016/j.chemosphere. 2016.09.081.

Jakobi, G. and Lçhr, A. 1987. Detergent ingredients. In: Gerhartz, W.(ed), *Ullmanns Encyclopedia of Industrial Chemistry*, 5 ed. VCH,Weinheim, pp 338-372.

Jamaly, S., Giwa, A. and Hasan, S.W. 2015. Recent improvements in oily wastewater treatment: progress, challenges, and future opportunities. *Journal of Environmental Sciences* 37:15-30, doi:10.1016/j.jes.2015.04.011.

Jimenez, L., Breen, A., Thomas, N., Federle, T.W. and Sayler, G.S. 1991. Mineralization of linear alkylbenzene sulfonate by a 4-member aerobic bacterial consortium. *Applied and Environmental Microbiology* 57:1566-1569, doi:10.1128/aem.57.5.1566-1569.1991.

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Khleifat, K.M. 2006. Biodegradation of sodium lauryl ether sulfate (SLES) by two different bacterial consortia. *Current Microbiology* 53(5):444-448, doi:10.1007/s00284-006-0266-4.

Miller, J.H. 1972. *Experiment in Molecular Genetics*. Cold Spring Harbor Laboratory Press, New York.

Najim, A.A., Ismail, Z.Z. and Hummadi, K.K. 2022. Biodegradation potential of sodium dodecyl sulphate (SDS) by mixed cells in domestic and non-domestic actual wastewater: Experimental and kinetic studies. *Biochemical Engineering Journal* 180:108374, doi:10.1016/j.bej.2022.108374.

Naveenkumar, S., Manoharan, N., Ganesan, S., Manivannan, S. and Velsamy, G. 2010. Isolation, screening in vitro mutational assessment of indigenous soil bacteria for enhanced capability in petroleum degradation. *International Journal of Environmental Sciences* 1(4):0976-4402.

Odahara, T. 2004. Stability and solubility of integral membrane proteins from photosynthetic bacteria solubilized in different detergents. *Biochimica et Biophysica Acta* 1660:80-92, doi:10.1016/j.bbamem.2003.11.003.

Paulo, A.M.S., Aydin, R., Dimitrov, M.R., Vreeling, H., Cavaleiro, A.J., García- Encina, P.A., Stams, A.J.M. and Plugge, C.M. 2017. Sodium lauryl ether sulfate (SLES) degradation by nitrate-reducing bacteria. *Applied Microbiology and Biotechnology* 101(12):5163-5173, doi:10.1007/s00253-017-8212-x.

Peressutti, S.R., Olivera, N.L., Babay, P.A., Costagliola, M. and Alvarez, H.M. 2008. Degradation of linear alkylbenzene sulfonate by a bacterial consortium isolated from the aquatic environment of Argentina. *Journal of Applied Microbiology* 105:476-484, doi:10.1111/j.1365-2672.2008.03771.

Prats, D., Lopez, C., Diana, V., Pedro, V. and Leon, V.M. 2006. Effect of temperature on biodegradation of linear alkyl benzene sulfonate and alcohol ethoxylate. *Journal of Surfactants and Detergents* 9:69-75, doi:10.1007/s11743-006-0377-8.

Qiao, K., Tian, W., Bai, J., Zhao, J., Du, Z., Song, T., Chu, M., Wang, L. and Xie, W. 2020. Removal of high-molecular-weight polycyclic aromatic hydrocarbons by a microbial consortium immobilized in magnetic floating biochar gel beads. *Marine Pollution Bulletin* 159:111489, doi:10.1016/j.marpolbul.2020.111489.

Ran, Z., Zhu, J., Zhou, L. and Ji, R. 2016. Study on degradation kinetics of co-metabolic biodegradation of linear alkylbenzene sulfonate strains. *International Forum on Energy, Environment and Sustainable Development* 75:1071-1074, doi:10.2991/ifeesd-16.2016.192.

Schulz, S., Dong, W., Groth, U. and Cook, A.M. 2000. Enantiomeric degradation of 2-(4-sulfophenyl) butyrate via 4-sulfotechol in *Delftia acidovorans* SPB1. *Applied and Environmental Microbiology* 66:1905-1910, doi:10.1128/AEM.66.5.1905-1910.2000.

Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Marinas, B.J. and Mayes, A.M. 2008. Science and technology for water purification in the coming decades. *Nature* 452:301-310, doi.org/10.1038/nature06599.

Shu, W.C. and Ding, W.H. 2005. Determination of fluorescent whitening agents in laundry detergents and surface waters by solid-phase extraction and ion-pair high-performance liquid chromatography. *Journal of Chromatography A* 1088(1-2):218-223, doi:10.1016/j.chroma.2005.01.032.

Singh, A., Van Hamme, J.D. and Ward, O.P. 2007. Surfactants in microbiology and biotechnology. *Biotechnology Advances* 25(1):99-122, doi:10.1016/j.biotechadv.2006.10.004.

Tamura, K., Dudley, J., Nei, M. and Kumar, S. 2007. MEGA4: Molecular evolutionary genetics analysis (M.E.G.A). *Molecular Biology and Evolution* 24(8):1596-1599, doi:10.1093/molbev/msm092.

van Ginkel, C.G. 1996. Complete degradation of xenobiotic surfactants by consortia of aerobic microorganisms. *Biodegradation* 7:151-164, doi:10.1007/BF00114627.

Wong, J.W.C., Lai, K.M., Wan, C.K., Ma, K.K. and Fang, M. 2002. Isolation and optimization of PAHS degradative bacteria from contaminated soil for PAHs bioremediation. *Water, Air and Soil Pollution* 139:1-13, doi:10.1023/A:1015883924901.

Yadav, J.S., Lawrence, D.L., Nuck, B.A., Federle, T.W. and Reddy, C.A. 2001. Biotransformation of linear alkylbenzene sulfonate (LAS) by *Phanerochaete chrysosporium*: oxidation of alkyl side-chain. *Biodegradation* 12:443-453, doi:10.1023/A:1015056530264.

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