

Factors Affecting the Degradation of Linear Alkylbenzene Sulfonate by TiO₂ Assisted Photocatalysis and Its Kinetics

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Abstract

This research aims to study photocatalytic degradation of linear alkylbenzene sulfonate (LAS) in synthetic solution and industrial laundry wastewater by UV/TiO₂ process. The structural and surface properties of Degussa P25 TiO₂ powder were measured by X-ray diffractometer (XRD) and Autosorb, respectively. Factors affecting the photocatalytic decomposition i.e. pH, TiO₂ dosage, irradiation time, initial LAS concentration were investigated in a batch reactor. The kinetic of LAS degradation was studied at room temperature. After degradation, byproduct formation was analyzed using GC-MS. The experimental results showed that a dominating crystalline structure of TiO₂ was the tetragonal anatase phase (82.58%). The TiO₂ had a surface area of 77.79 m²/g, a pore size of 14.38 nm in diameter and a pore volume of 0.28 cc/g. It was found that the optimum conditions for photocatalytic degradation of LAS were at initial LAS concentration of 20 mg/L, non-adjust pH (pH 5.5), TiO₂ dosage of 100 mg/L with irradiation time for 60 mins. Under these conditions, the removal efficiency of LAS in the synthetic solution reached 83.20%. The removal of LAS follows the second order kinetic with rate constant of 0.0031 L/mg/min and half-life of 16.13 min. Alkyl long chains, carboxylic acids and aromatic rings were detected as its degradation products. The removal efficiencies of LAS, orthophosphates and COD in industrial laundry wastewater were 51.99±7.36%, 45.98±4.85 % and 16.00±0.00%, respectively.

Keywords: degradation products; kinetics, linear alkylbenzene sulfonate, photocatalysis, TiO₂

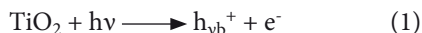
1. Introduction

Linear alkylbenzene sulfonate (LAS) is one of the most common anionic surfactants used in synthetic detergents. It consists of an aromatic ring sulfonated at the para position and attached to a linear alkyl chain at any internal carbon atom. Its commercial products are mixture of homologues of different alkyl chain lengths ranging from 10 to 13 carbon atoms (C_{10} - C_{13}) and different phenyl positional isomers in proportions (OECD, 2005). These lead to different physical and chemical properties. According to its structure containing polar head and non-polar hydrophobic tail, LAS has good cleaning or solubilisation properties. In addition, it has low to moderately toxicity, non-bioaccumulation, readily biodegradability and low cost (Vives- Rego et al., 2000). Nowadays, it is widely used in both household detergents and various industrial applications (Tolls et al., 1997).

LAS is easily biodegraded under aerobic conditions. The oxidative pathway is initiated by an ω -oxidation of the terminal alkyl chain and followed by β -oxidations. This results in a formation of sulfophenyl carboxylic acids (SPC) as intermediates (Eichhorn and Knepper, 2002). Then, the benzene ring is cleaved and desulfonated to carbon dioxide (CO_2), sulfate (SO_4^{2-}) and water (H_2O), respectively (Szabo- Bardos et al., 2011). However, LAS is not effectively degraded under anaerobic conditions (Garcia et al., 2005). Therefore, it is generally detected as a constituent of municipal and industrial

wastewaters (Holt et al., 1998). Previous research indicated that low concentrations of LAS were toxic to certain fish, aquatic animals and aquatic plants including bacteria and algae (Abd El-Gawad, 2014). Normally, LAS concentration in natural water ranged between 0.02 and 1.0 mg/L can be harmful to fish gills (Koparal et al., 2006). Therefore, the use of LAS has been limited and banned in several countries in Europe, various US states, Canada and Japan. However, a large quantity of LAS has been consumed for decades in many developing countries including Thailand (Venhuis and Mehrvar, 2004). Several treatment methods have been considered for LAS removal from wastewater. The chemical treatment is commonly applied but it is expensive and has precipitates in the process. While the biological treatment is inexpensive, it has low efficiency and is time-consuming (Ramcharan and Bissessur, 2017). Titanium dioxide (TiO_2) assisted photocatalytic process is one of the advanced oxidation processes, which is increasingly used for degradation of low concentration of organic compounds. It gradually breaks down the contaminant molecules so there is no sludge produced. TiO_2 is commonly used as a photocatalyst because it is nontoxic, photochemical stable, insoluble in water and low cost (Zhang et al., 2011).

When TiO_2 is exposed with UV irradiation, it generates electron (e^-) from the valance band and positive hole (h^+) from the conduction band (Eq.1).



Hydroxyl radicals (OH[•]), superoxide radical anions (O₂^{•-}), hydroperoxy radicals (HO₂[•]) are produced and then oxidized with LAS resulting in formation of organic compounds, CO₂, SO₄²⁻ and H₂O (Lea and Adesina, 1998). Szabo-Bardos et al. (2011) suggested a possible degradation pathway of benzene sulfonate in photocatalytic oxidation as shown in Figure 1.

The removal efficiency of LAS with TiO₂ photocatalysis depends on TiO₂ concentration, pH value, dissolved oxygen, dissolved cationic ions and dissolved organic matters. However,

there is some interference of anionic ions that compete with organic pollutants to absorb on TiO₂ surface (Ghanbarian et al., 2011; Chen and Liu, 2007). According to the zero-point charge (pzc) value of TiO₂ (pH 6.25), the TiO₂ surface is positively charged in acidic solution (pH < 6.25) while it is negative charged in alkaline solution (pH > 6.25) as illustrated in Eq. (2-3) (Boyjoo et al., 2012).

When, pH < 6.25:



pH > 6.25:

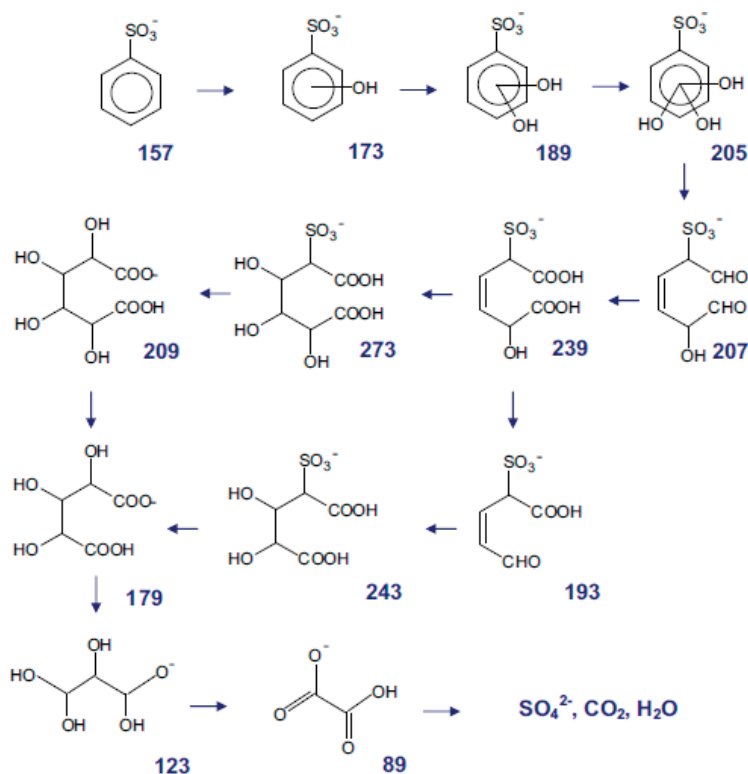


Figure 1. A possible degradation pathway of benzene sulfonate in photocatalytic oxidation proposed by Szabo-Bardos et al. (2011). The numbers indicate the m/z values of the corresponding species.

Under acidic conditions, the positive charge of TiO₂ could attract more anionic groups of surfactants to its surface. While under basic conditions, there was a coulombic repulsion force between negatively charged surface of catalyst and the hydroxide anions (Sanchez et al., 2011).

Although several research studies have investigated the removal efficiency of LAS by TiO₂ photocatalysis, few studies have determined on the degradation products of the reactions (Terechova et al., 2014). The objectives of this study are to investigate factors influencing the degradation of LAS in synthetic solution by TiO₂ photocatalysis (i.e. pH, TiO₂ dosage, UV irradiation time, initial LAS concentration), to determine degradation products of LAS obtained from photocatalysis and to study kinetics of a chemical reaction of photocatalytic process. The removal efficiencies of LAS, orthophosphate and COD in industrial laundry wastewater were also examined under the optimum conditions from the experiment.

2. Materials and Methods

2.1 TiO₂ powder and reagents

Degussa P25 TiO₂ (CAS no. 13463- 67-7), obtained from College of Nanotechnology KMITL, was used as a photocatalyst. The crystal phase compositions of TiO₂ powder were measured by X-ray diffractometer (XRD) (Bruker, model SRS 3400, Germany) with Cu-K α radiation ($\lambda=1.5406 \text{ \AA}$) Data were taken

in the 2θ scan range of 10° to 70° with a step of 0.04° and 1 second per step. The structure of TiO₂ powder was examined in terms of crystalline dimensions. The crystallite diameter was calculated from the peak width of the diffractograms by the Scherrer's equation (Kavei et al., 2011). The surface area, pore volume and pore size were measured by Autosorb (Autosorb-1, Quantachrome, USA). The surface area was calculated by the BET measurements from the nitrogen adsorption isotherms.

A LAS stock solution of 1,000 mg/L was prepared from sodium dodecyl benzene sulfonate (88%, Sigma Aldrich, USA). A LAS concentration of 20 mg/L was used as the synthetic solution. All chemical reagents used in this study were analytical grade and HPLC grade. Deionized water, used to prepare the solutions, was supplied by a Milli-Q water purification unit (ROM- 250-100T, Treat Chemical Co., Ltd).

2.2 Photocatalytic reactor

A photocatalytic reactor was made from a rectangular wood box (72 cm length x 58 cm width x 66 cm height). Inside walls were covered with white paper to prevent UV adsorption on the walls. The radiation source was a 18 watts UV-C lamp (Narwar, India) with dimension of 58.87 cm length x 2.55 cm diameter and a wavelength of 254 nm. Four UV-C lamps were positioned on the the ceiling of the reactor with 20 cm distance from the surface of solution.

A magnetic stirrer (Fisher Scientific, USA) was applied to achieve well-mixing of TiO₂ particles in the solution. A schematic of the photocatalytic reactor is shown in Figure 2.

2.3 Experimental procedure

2.3.1 Study of influencing factors on photocatalytic degradation

The experimental procedure was adapted from the work of Terechova et al. (2014) and Ghanbarian et al. (2011). Batch experiments were carried out in a 600 mL beaker placed in the photocatalytic reactor under ambient temperature. A concentration of 100 mg/L TiO₂ was introduced into 100 mL of the solution containing 20 mg/L of LAS and then equilibrated by sonicating at 48 kHz for 10 min (Ultrasonik, Fisher Scientific, USA) in the dark condition. After that, the solution was simultaneously stirred under UV-C light at defined time intervals of 0, 30, 60 min. To determine the remained LAS, 100 mL of the suspension was taken and then filtered through a 0.45 µm microfiltration membrane to separate TiO₂ particles before analysis. LAS containing in the analyses was measured with the methylene blue active substance assay in Standard Methods for the Examination of Water and Wastewater (APHA, 1998). The use of adsorption on TiO₂ particles under dark condition and photolysis with UV-C irradiation for LAS removal was individually conducted using the same experimental procedures mentioned above. The experiments were conducted to study influencing factors

on TiO₂ assisted photocatalytic degradation of LAS i.e. pH, TiO₂ dosage, UV irradiation time and initial LAS concentration. pH levels were varied at 2, 4, 7 and non-adjust. Dosages of TiO₂ were varied at 100, 300, 500 mg/L. UV irradiation times were examined at time intervals of 5, 10, 15, 30, 60, 120 min. Initial concentrations of LAS were varied at 10, 20, 40, 60, 100 mg/L. Amounts of LAS degraded and sulfates formed were determined using methylene blue active substances assay (APHA, 1998) and turbidimetric method (US EPA, 1986), respectively. The removal efficiencies of LAS in industrial laundry wastewater were also examined under the experimental optimum conditions. Before and after TiO₂ photocatalysis, chemical oxygen demand (COD) and orthophosphate of the sample were determined by Standard Methods for the Examination of Water and Wastewater (APHA, 1998) and ascorbic spectrophotometric method (US EPA, 1978), respectively. The chemical kinetic on LAS removal was also studied. All sample measurements were run in triplicate. All result data were presented in mean ± standard deviation. One-way ANOVA and post-hoc Tukey's test were used to assess the mean differences at a significance level of 0.05.

2.3.2 Determination of degradation products

Under the optimum conditions, degradation products after photocatalysis were analyzed using GC-MS. The sample was prepared using a modified method of Moldovan et al. (2011). The C-18 SPE cartridge (Phenomenex, USA)

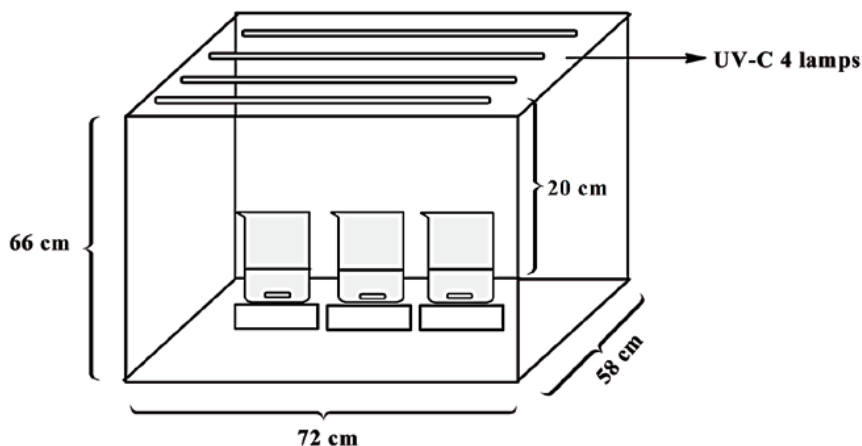


Figure 2. A schematic diagram of the photocatalytic reactor

was conditioned with 6 mL of methanol : DI water (1:1 v/v). Each of 100 mL sample was transferred through the cartridge. After sample loading, the cartridge was rinsed with 1 mL DI water and then dried under vacuum. The residue was eluted with 2.5 mL methanol (HPLC grade). Degradation products of LAS were determined by a HP-6890N gas chromatograph coupled with a HP- 5973N mass spectrometer (Agilent Technologies, USA). GC was operated in splitless mode. 2 μ l of each sample was injected onto a HP-5MS GC fused-silica capillary column, 30 m x 0.25 mm I.D. x 0.25 μ m film thickness, 5% diphenyl and 95% dimethyl siloxane copolymer (J&W Scientific, USA). Helium (99.999% purity, Praxair, Thailand) was used as a carrier gas at a flow rate of 1.0 mL/min.

The GC oven was programmed from 90 °C (initial temperature), held at 90 °C for 2 min, to 120 °C at 10 °C/min, then increased to 200 °C at 3.5 °C/min, and increased from 200 °C to 315 °C

at 5 °C/min, holding at 315 °C for 11 min. The transfer line between the GC and MS was operated at 315 °C. The MS was operated in electron impact (EI) mode at 70 eV with a mass range of 30-500 amu and filament/ multiplier delay 4 min. The MS analysis was performed using the total ion chromatogram mode. Chromatograms of sample were identified by comparison of mass spectra obtained from the NIST mass spectral library database. The substance quantities were determined according to the chromatographic peak areas.

3. Results and Discussion

3.1 Characteristics of TiO_2

The X-ray diffraction pattern of the Degussa P25 TiO_2 particles is shown in Figure 3. The peaks of TiO_2 particles were identified by comparison with JCPDS 71- 1166 (Kavei et al., 2011) and 75-1757 (da Silva et al., 2015) according to 2θ which confirmed anatase and

rutile phases, respectively. The diffractograms of TiO₂ particles confirmed anatase structure (2 θ) at 25.40° and 48.08° whereas the 2 θ peak at 27.36° confirmed its rutile structure. The intensity of XRD peaks of the sample implies that the particles are tetragonal crystal system. The structural and surface properties determined by XRD and Autosorb are illustrated in Table 1. The TiO₂ particles had BET surface area of 77.79 m²/g, a pore size of 14.38 nm in diameter and a pore volume of 0.28 cc/g. It contained anatase 82.58% and rutile 17.42%. It implies that TiO₂ containing a mixture of major anatase phase and minor rutile phase could enhance higher photocatalytic activity because the anatase phase has slightly higher electrochemical potential for electrons than the rutile phase. This leads to lower capacity to adsorb oxygen and higher degree of hydroxylation (Tanaka et al., 1991). It is consistent with the result of He et al. (2013) which found that anatase/rutile phase ratio of 80:20 was the effective separation of the photo generated electron-hole pairs.

3.2 *Influencing factor on photocatalytic degradation*

The removal efficiencies of LAS were carried out with 100 mL of initial LAS concentration of 20 mg/L and a TiO₂ concentration of 100 mg/L in a presence of UV-C light (254 nm) 72 watts for photocatalysis and without a presence of UV-C light for adsorption. The photolysis of LAS by UV-C without the presence

of TiO₂ was also investigated. These results are shown in Figure 4. About 20% of LAS was adsorbed on the TiO₂ surfaces because the particles had small surface area as illustrated in Table 1. The adsorption of LAS on the surfaces tended to increase over a short period of time (30 min), but it was slightly reduced at higher contact time (60 min). It should be possible to explain that LAS is likely desorbed from the surface of LAS. In addition, chemical adsorption can be negligible because a stereochemical configuration of LAS is unsuitable to chelate with TiO₂ (Ghanbarian et al., 2011). The results showed that UV-C radiation (254 nm, 72 watts) could not degraded LAS. It was found that the removal efficiency of LAS by TiO₂ photocatalysis was significantly higher than the other methods at p-value of <0.001. It tended to increase with increasing irradiation time. Around 90% of the initial amount of LAS was degraded after photocatalysis for 60 min. When TiO₂ surface is exposed to UV-C irradiation, it starts to generate electron (e⁻) from the whereas CO₂ and sulfate could not be detected by GC-MS. In this shown in Eq. 1. Hydroxyl radicals (OH^{*}), superoxide radical anions (O₂⁻), hydroperoxy radicals (HO₂^{*}) are produced. Subsequently, LAS was oxidized to organic compounds, carbon dioxide, sulfate and water (Szabo-Bardos et al., 2011; Etacheri et al., 2015). It can be noted that TiO₂ - induced photocatalysis at UV-C 254 nm is an effective process for LAS degradation. This is consistent with the results of Ghanbarian et al. (2011). In photocatalytic process, the effect of pH,

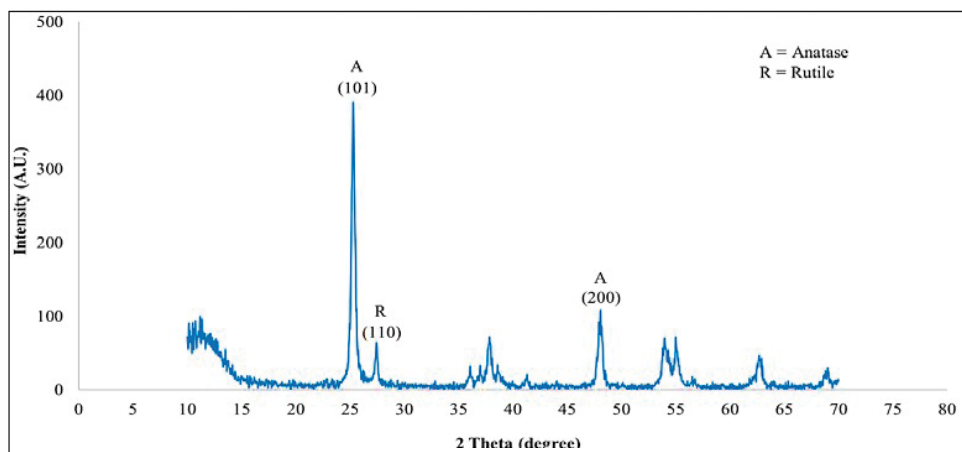


Figure 3. XRD pattern of the Degussa P25 TiO₂ powder.

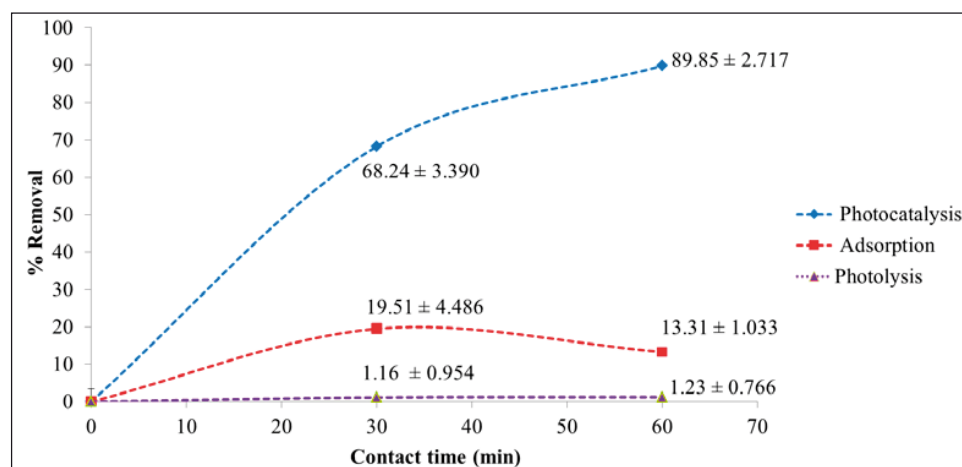


Figure 4. Comparison on removal efficiencies of LAS by photocatalysis (TiO₂ 100 mg/L with UV-C 254 nm, 72 watts), adsorption (TiO₂ 100 mg/L) and photolysis (UV-C 254 nm, 72 watts)

Table 1. Characteristics of TiO₂ determined by XRD and Autosorb.

Characteristics	Values
Anatase (%)	82.58
Rutile (%)	17.42
Crystalline structures	Tetragonal
Surface area (m ² /g)	77.79
Pore volume (cc/g)	0.28
Pore size (nm)	14.38

TiO₂ dosage, UV irradiation time and initial LAS concentration was investigated by varying pH from 2 to 7 and non adjust, TiO₂ concentrations between 100 and 500 mg/L, irradiation times from 5 to 120 min and initial LAS concentrations between 10 and 100 mg/L. The effect of pH in LAS removal efficiency is shown in Figure 5(a). In this work, the basic conditions were not observed because at pH > pzc (6.25), TiO₂ surface is negatively charged (Eq. 3) and should repel LAS which is negative ions. The removal of LAS in both acidic and natural solution was not significantly different at pvalue of 0.178. This may be because pH of solution tended to slightly reduce due to the formation of acidic byproducts of the reaction e.g. CO₂, SO₄²⁻ (Szabo-Bardos et al., 2011). The removal efficiency of LAS at non-adjust pH (5.5) was 72.32%. Figure 5 (b) presents that the removal of LAS slightly increased with increasing TiO₂ dosage. However, the mean difference of TiO₂ concentration between 100 and 500 mg/L was not significant at pvalue of 0.109. Around 75% of LAS was removed with 100 mg/L of TiO₂ because there was available surface area of TiO₂ due to its low initial LAS concentration. However, the excess dosage of TiO₂ may result in decreasing removal efficiency of LAS because it increases the opacity which prevents UV light passing through the solution (Sugiharto et al., 2014). Figure 5 (c) shows that the removal of LAS dramatically increased when increased irradiation time

(p-value = 0.007). However, the mean difference of irradiation time between 60 and 120 min was not significant at p-value of 0.730. This can be explained that LAS is adsorbed on the TiO₂ surface while OH radicals are generated by UV-C light at the same surface. Then, the molecules of LAS are attacked by the OH radicals. The longer irradiation time, the higher levels of OH radicals are generated (Lea and Adesina, 1998). About 83% of LAS were decomposed at irradiation time of 60 min. Figure 5 (d) illustrates that the degradation efficiency tended to decrease with increasing initial concentration of LAS (p-value < 0.001). It should be explained that the initial concentration of LAS is increased, they are adsorbed on the TiO₂ surface resulting in decrease in formation of hydroxyl radical and photon. However, the mean difference of LAS concentrations between 20 and 40 mg/L was not significant at pvalue of 0.988. This result corresponds with the work of Samadi et al. (2014). Figure 6 indicates that the concentration of LAS tended to decrease while the concentration of sulfate ions tended to increase. The concentrations of LAS decreased from 19.08 mg/L to 3.206 mg/L whereas the concentration of sulfate ions increased slowly from 0 mg/L to 1.18 mg/L and then rapidly increased from 1.18 to 8.62 mg/L. This is because long chain hydrocarbons of LAS are primarily degraded and then sulfonate are oxidized to form sulfate ions as described in Eqs. 4-7. This is consistent with the work of Fernández et al. (2004).

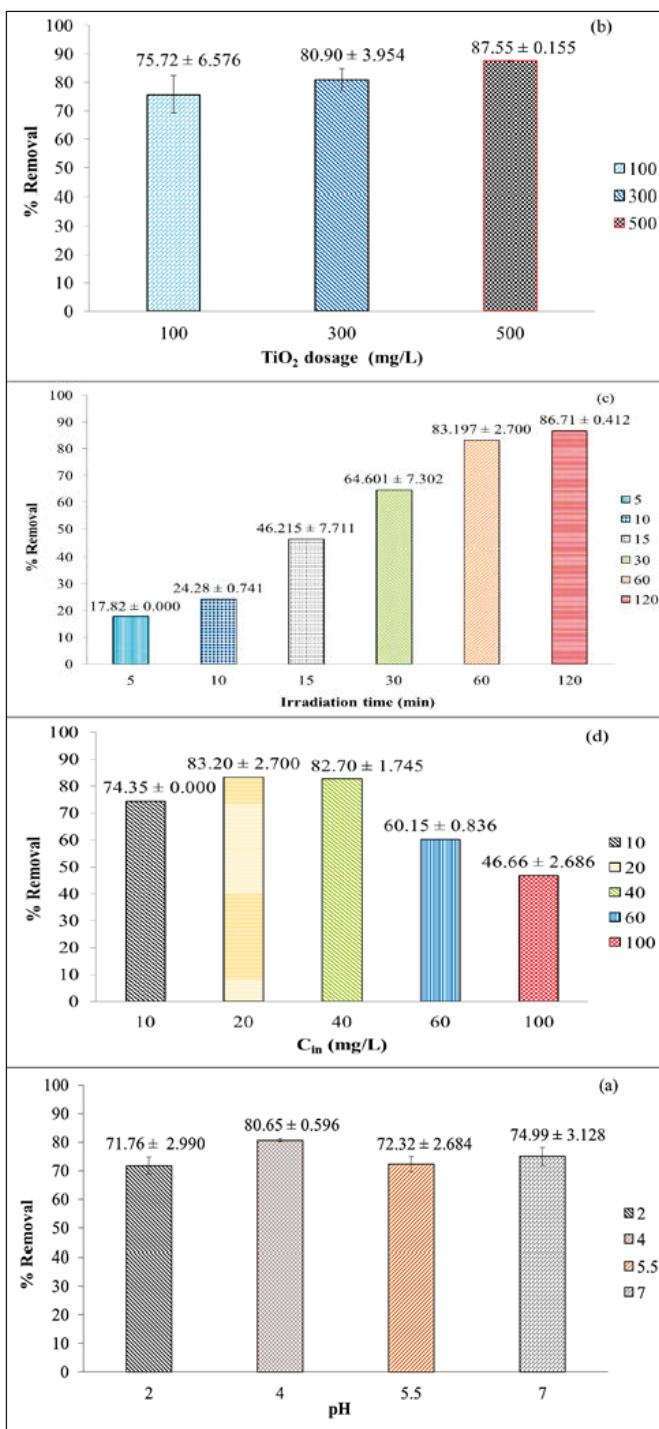


Figure 5. The influencing factors on the removal of LAS (a) effect of pH (2-7), (b) effect of TiO₂ dosage (100-500 mg/L), (c) effect of irradiation time (5-120 min), (d) effect of initial concentration of LAS (10- 100 mg/L)

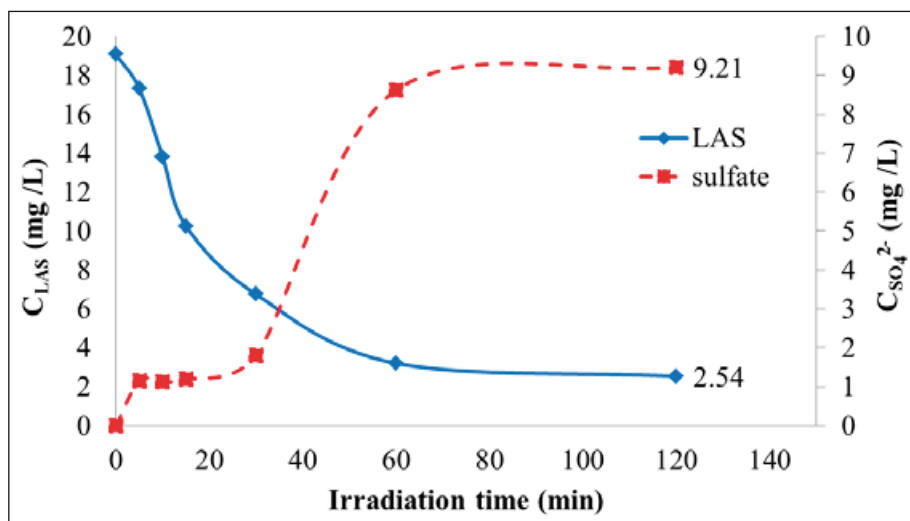
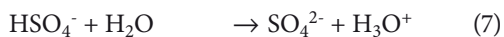
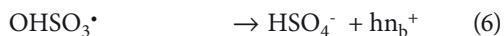
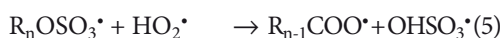
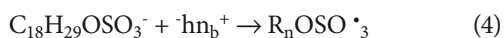


Figure 6. The relation between LAS degradation and sulfate formation in the reaction.



3.3 Chemical kinetic of LAS removal

The results indicate that the experimental data were fitted to a second order kinetic model as illustrated in 2 and Figure 7. It can be described that the reaction rate depends on the concentrations of LAS and TiO₂. This is consistent with the work of Sanchez et al. (2011) reported that the second order kinetic model fitted to initial LAS concentrations of higher than 15 mg/L. At 20 mg/L of LAS, rate constant (K) and half-life for LAS degradation were 0.0031 L/ mg/ min and 16.13mins, respectively.

In the experiment, the photocatalytic reaction time of 15 min could degrade 10.26 mg/L of LAS, which is close to half-life from calculation (16.13 min).

3.4 Degradation products of LAS determined by GC-MS

MS are illustrated in Table 3. Alcohols, aldehydes and peroxides were not found because they were quickly degraded (Maryani and Kustiningsih, 2015) whereas CO₂ and sulfate could not be detected by GC-MS. In this study, the fragmentation of degradation products from mass spectrum (m/z) was corresponding with the results of Ding et al. (1998) and Moldovan et al. (2011). These results indicate that LAS is possibly degraded to nontoxic and less toxic compounds (Szabo-Bardos et al., 2011). However, the toxicity tests are required in future work.

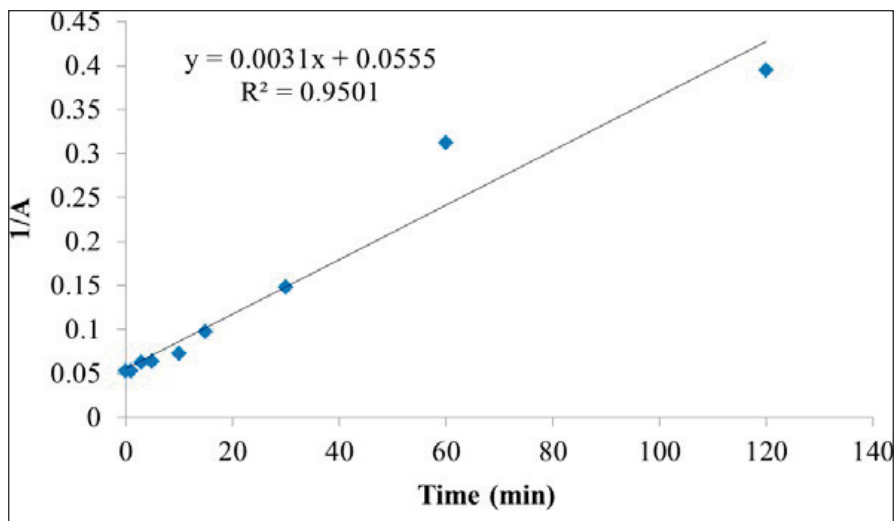


Figure 7. Second order kinetic model for TiO₂ 100 mg/L and LAS 20 mg/L with UV-C 72 watts

Table 2. The chemical kinetics on removal of linear alkyl benzene sulfonate by TiO₂ photocatalysis.

	Zero Order	First Order	Second Order
Eq.	$Y = -0.138X + 15.556$	$Y = -0.0018x + 2.7518$	$Y = 0.0031x + 0.0555$
R ²	0.7335	0.8749	0.9501
Rate law diff.	$r = k$	$r = k [A]$	$r = k [A]^2$
Rate law integ.	$[A] = -kt + [A]_0$	$\ln [A] = -kt + \ln [A]_0$	$1/[A] = kt + 1/[A]_0$
Rate constant (K)	0.138	0.0018 min ⁻¹	0.0031 L/mg/min
Half -life	72.46 min	38.50 min	16.13 min

3.5 Removal efficiency of LAS in industrial laundry wastewater

The characteristics of industrial laundry wastewater before and after TiO₂ photocatalysis are shown in Table 4. About 52% of LAS-containing wastewater with initial concentration of 2.88 mg/L was removed by TiO₂ photocatalysis under the optimum conditions from the experiment. The chemical oxygen demand (COD) slightly decreased from 131.55 to 110.50 mg/L with efficiency of 16%. The removal efficiency

of orthophosphate was about 46%. The removal efficiency of LAS was lower than that of the synthetic wastewater. This may be caused by interferences of anionic ions such as phosphate ions in industrial laundry wastewater compete with LAS to absorb on surface of TiO₂ (Ghanbarian et al., 2011; Chen and Liu, 2007). Ghanbarian et al. (2011) reported that the adsorbed anions (e.g . Cl⁻, NO₃⁻, SO₄²⁻, CO₃²⁻, HCO₃⁻) could compete against organic contaminants for the radical species (OH[•], O₂⁻, HO₂[•]) on the surface of catalyst and prevent the photocatalytic degradation

Table 3. Byproducts of LAS after TiO₂ photocatalysis

Peak No.	Compound name	Molecular formula	RT (min)	m/z	% Total area	Quality
1	Hydroxyacetic acid	C ₁₆ H ₂₂ O ₄	4.26	31, 29, 45	0.322	45
2	1, 2, 3 Propanetriol triacetate	C ₉ H ₁₄ O ₆	8.49	43, 103, 145	0.958	83
3	2, 4-Di-tert-butylphenol	C ₁₄ H ₂₂ O	12.73	191, 57, 206	0.412	86
4	Heneicosane	C ₂₁ H ₄₄	21.12	57, 43, 71	0.175	90
5	Diisobutyl phthalate	C ₁₆ H ₂₂ O ₄	22.74	149, 57, 29	0.092	72
6	Methyl hexadecanoate	C ₁₇ H ₃₄ O ₂	24.63	74, 87, 43	0.132	93
7	Dibutyl phthalate	C ₁₆ H ₂₂ O ₄	25.35	145, 205, 167	0.758	90
8	Bis(2-ethylhexyl) adipate	C ₂₂ H ₄₂ O ₄	34.93	129, 57, 112	7.956	95
9	Diisooctyl phthalate	C ₂₄ H ₃₈ O ₄	37.35	149, 167, 279	89.197	90

Table 4. The characteristics of industrial laundry wastewater

Characteristics	Concentrations		
	Industrial laundry wastewater	After treatment with TiO ₂ photocatalysis	% Removal
pH	7.38	6.82	
LAS (mg/L)	2.879±0.094	1.382±0.212	51.99±7.36 %
Orthophosphate (mg PO ₄ ³⁻ /L)	10.61±2.946	5.732±0.514	45.98±4.85 %
COD (mg/L)	131.55±2.813	110.50±0.000	16.00±0.00 %

4. Conclusion

This study found that UV irradiation time and initial concentration of LAS affected the removal efficiency of LAS. However, pH ranges from 2 to 7 and TiO₂ dosage from 100 to 500 mg/L did not affect the LAS degradation. TiO₂ photocatalysis could degrade LAS to become alkyl long chains and carboxylic acids and aromatic ring. The removal of LAS follows the second order kinetic with rate constant (K) of 0.0031 L/mg/min and half-life of 16.13 min. LAS contained in industrial laundry wastewater was able to be degraded by TiO₂ photocatalysis; however, LAS removal efficiency was interfered with other contaminated anions in the wastewater.

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