

# Wastewater Treatment Technologies Used for the Removal of Different Surfactants: A Comparative Review

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## Abstract

The presence of compounds such as surfactants, which are difficult to degrade by conventional, chemical and/or biological methods, has imposed the growth of efficient water-treatment processes. Apprehensions over the globally disseminated surfactants are growing because these surfactants are environmentally tenacious and bioaccumulative. A solution for the removal of these recalcitrant surfactants has involved wide-ranging examinations in the field of advanced oxidation processes (AOP). In these chemical oxidation processes, reaction mechanisms include the change in structure, and chemical properties of the organic substances, where molecules break into smaller fragments. Unlike conventional methods, chemical oxidation processes entirely eliminate the surfactants by mineralizing and breaking down the organic compound to form carbon dioxide and water.

**Keywords**— surfactants; wastewater treatment technologies; chemical oxidation; removal efficiency

## I. INTRODUCTION

Surfactants, or surface-active compounds, are organic molecules that contain both hydrophobic groups (their tails) and hydrophilic groups (their heads). Surfactants are used to lower the surface tension between two liquids or between a solid and liquid, which makes them suitable as detergents, wetting agents, emulsifiers, foaming agents, and dispersants [1]. The hydrophobic part is usually the equal of 10 to 20 carbon atoms [2]. This part can be aliphatic, aromatic, or a combination of both. The

hydrophilic clusters give the principal classification to surfactants, which are non-ionic, anionic, cationic or zwitterionic.

Surfactants are profoundly used in detergents, shampoos, dishwashing liquids, cosmetics, pesticides and other consumer product formulations. Surfactants are also used significantly in industries such as textiles, fibers, food, paints, polymers, pharmaceuticals, microelectronic, mining, oil recovery, pulp-paper industries, etc. They are among the broadly dispersed xenobiotics that may enter waste streams and aquatic environment.

Surfactants cause changes in the ecosystem. They are harmful to human-beings, fish and vegetation, and they are also responsible for the foams in rivers and other water sources [3]. Surfactants are in widespread use throughout the world, and are gradually increasing day by day. As a result, regulatory authorities have fixed strict limits for the amount of surfactants present in water sources. Consequently, it is pertinent to study and identify effective treatment methods for the removal these organic pollutants from wastewaters. There are various technologies that have been studied and employed to treat surfactant-containing wastewaters, to eliminate them from effluents completely. Once the surfactants are released into wastewaters, they are treated biologically. However, surfactants are resistant to most of the conventional physico-chemical treatment methods. As a result, the toxicity and environmental perseverance of these surfactants are emerging concerns. This paper aims to review and compare the different technologies that have been used for the removal of surfactants from wastewater.

The main objective of this review is to study and compare the different methods that have been used for treating wastewaters containing surfactants. Based on the review, a safe, cost effective and practical method for the degradation of surfactants used in chemical enhanced oil recovery (CEOR) discharged produced water will be recommended.

## **II. STRUCTURE AND CHARACTERISTICS OF SURFACTANTS**

The hydrophobic part of a typical surfactant molecule is made up if either linear or branched alkyl chain with 10-20 carbon atoms [2, 4]. Some surfactants may also contain an aryl group in the hydrophobic part [1], [4]. The class of the surfactant is determined by the structure of the hydrophilic part (head), is divided into anionic, cationic, non-ionic and zwitterionic. The surfactant molecules vary among the classes.

Anionic surfactants are negatively charged in aqueous solutions. This class represents the majority of surfactants that are in use. The negative charge of the anionic surfactants in aqueous solutions originates from sulfate, sulfonates or carboxylate groups [1, 5-7]. Some examples of the common anionic surfactants are linear alkylbenzene sulfonates (LAS), alkyl benzene sulfonate (ABS), alcohol ether sulfates, and fatty alcohol sulfates, sodium dodecyl sulfate (SDS), etc. [5 -7].

Cationic surfactants are positively charged in aqueous solutions. A large proportion of this class links to nitrogen compounds such as fatty amine salts and quaternary

ammoniums (QAC) [5 - 6]. Some of the commonly used cationic surfactants are alkyl ammonium chlorides, alkyl trimethylammonium, alkyl benzyl dimethylammonium compounds, etc.

Non-ionic surfactants do not ionize in aqueous solutions because their hydrophilic part is non-dissociable, and some examples of the hydrophilic part are alcohol, phenol, ether, ester, or amide. The hydrophobic part of non-ionic surfactants is often of the alkyl or alkylbenzene type [5, 7].

Zwitterionic Surfactants, also known as amphoteric surfactants, possess both a positive and a negative charge on their hydrophilic end, giving them a net charge of zero. These surfactant molecules exhibit both anionic and cationic dissociations. Some examples of this class of surfactants are synthetic products like betaines or sulfobetaines and natural substances such as aminoacids and phospholipids [6 - 7].

### ***Environmental Impacts of Surfactants***

The biodegradability of surfactant molecules is dependent on the class of the surfactant, the length of chain in the hydrophilic and hydrophobic group, types of functional groups, structures of the chains, and the type of treatment for the removal of the surfactant. Most of the surfactants currently in use are synthetic organic compounds, therefore making them xenobiotic [4]. Majority of these surfactants are considered to be relatively biodegradable, both aerobically and anaerobically. However, surfactants comprising of an aryl ring or some quaternary ammonium surfactants are more resistant to eventual biodegradation. These surfactants or their partially degraded by-products are therefore still found in treated wastewaters, or digested sludge.

Recent studies have revealed that there are some effects to the health and environment by synthetic surfactants, as well as any of their degradation by-products. These effects are considered serious problems due to the toxic effect to aquatic life, as well as their potential to disrupt hormonal systems of these aquatic organisms. Some surfactants can only be partially degraded in the anaerobic environment to form alkylphenols. These alkylphenols are persistent, and have estrogenic activities to organisms such as fish [8]. Conventional physico-chemical and biological processes cannot easily treat wastewaters with large quantities of surfactants and high COD content [4, 5].

For example, anionic surfactants can bind to bioactive macromolecules such as peptides, enzymes, and DNA. This may change the folding of the polypeptide chain and the surface charge of a molecule, which may result in the modification of the biological function [4].

Cationic QACs are the most toxic, followed by amphoteric amine oxides that are also highly toxic [3, 4]. The primary target site of cationic surfactants is the cytoplasmic (inner) membrane of bacteria. QACs bind to inner membranes and disorganize them via their long alkyl chain [8].

Nonionic surfactants exert antimicrobial activity by binding to various proteins and phospholipid membranes. Such binding increases the permeability of membranes and vesicles, causing leakage of low molecular mass compounds. This can result in cell death or damage through loss of ions or amino acids [4, 8].

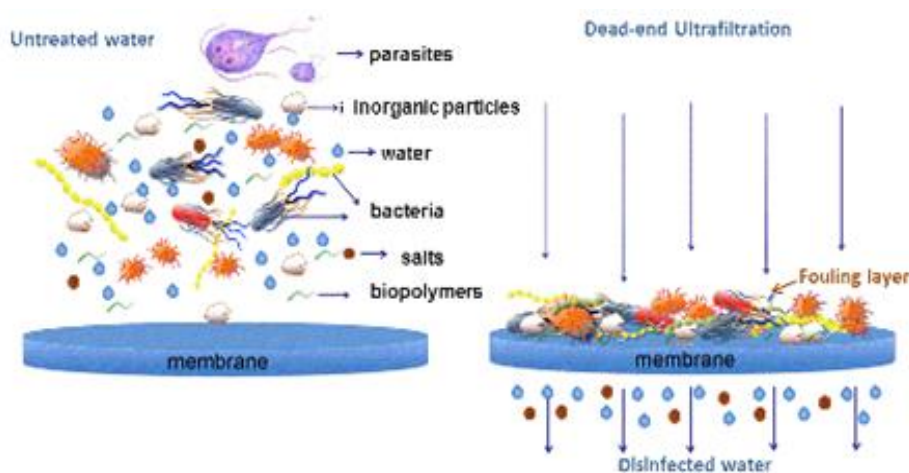
As a result, it can be concluded that higher concentrations of surfactants and their degradation products may affect organisms in the environment as well as causing denaturation of protein, hemolytic lesion and skin disease [13]. This reinforces the need to determine effective treatment techniques for completely eliminating surfactants from effluents.

### III. WASTEWATER TREATMENT METHODS USED FOR REMOVAL OF SURFACTANTS

The conventional methods for surfactant removal from the water environment involve processes such as chemical and electrochemical oxidation [9, 10], membrane technology [11–13], chemical precipitation [14–17], adsorption [18–20], photocatalytic degradation [21–27], and various biological methods [28]. The following subsections will review the effectiveness and efficiency for some of the methods employed for the treatment of surfactants.

#### *Membrane Filtration*

Membrane processes are increasingly employed in wastewater treatment for the removal of bacteria and other microorganisms, particulate material, micro-pollutants, and natural organic materials. Membranes are thin sheets of materials that are able to separate contaminants from water, by allowing water and dissolved salts to pass through them and retaining pollutant particles. Water treatment processes employ several types of membranes. They include microfiltration (M-F), ultrafiltration (U-F), reverse osmosis (R-O), and nanofiltration (N-F) membranes.



**Fig 1:** Scheme of Membrane Filtration [17]

Studies show that the material used for the membrane influences the separation of surfactant. Investigations conducted by Kowalska [10] showed that polysulphone and polyethersulphone yielded the best separation of anionic surfactants, which ranged at 71-91% at 5 kDa. Christa et al [11] determined that surfactant removal by nanofiltration membranes posed the least amount of problems (permeability, fouling, etc.). In their experiments, they were able to achieve higher than 95% TOC rejection coefficients for model solutions and only 92% for wastewater. Some reviews have shown that nanofiltration membranes are not, or only slightly affected by anionic or non-ionic surfactants. However, it has been determined that the maximum working temperature for some of the membranes is only up to 45°C. Transport and separation properties of membranes for surfactant solutions can be attributed to concentration, polarization, membrane fouling and interactions between the membrane and surfactant molecules [12-13]. Zhao et al. [13] found that the fouling caused by the surfactant was difficult to remove as the protein-surfactant complexes formed had a thick and compact structure, and accumulated or plugged in within the membrane, which was difficult to remove.

Filtration can provide satisfactory treatment and require less space needed than conventional treatment schemes. They have simple operation, and can be used to separate many kinds of contaminants. Disinfection of membranes can be performed without chemicals. Nevertheless, membrane fouling can pose a big problem and the membranes have to be replaced on a regular basis as it has been found in some instances that the fouling is difficult to remove. Therefore, regular change of membranes is required, which comes with a cost, as well as requiring a ready stock and storage of membrane filters. In addition, when using membrane filtration, there is generation of polluted water from that occurs as a result of backwashing. Membrane filtration processes are highly dependent on pressure and temperature.

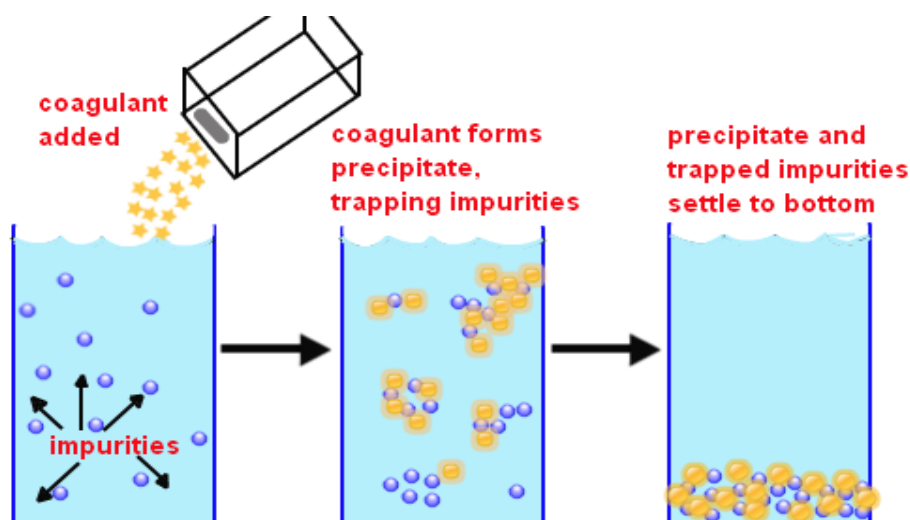
### ***Coagulation and Flocculation***

Coagulation-flocculation is a chemical water treatment technique that is typically applied prior to sedimentation and filtration. This process is used to enhance the ability of a treatment process to remove particles. Coagulation is a process that forms a mass large enough to settle or be trapped in the filter. Flocculation is gentle stirring or agitation to encourage the particles formed to cluster into masses large enough to settle or be filtered from solution. Aluminum sulfate (alum), ferrous sulfate, ferric chloride and ferric chloro-sulfate are examples of commonly used coagulants.

This method of treatment has been found to be effective for the removal of surfactants from wastewaters. In many studies, the removal of surfactants from wastewater was approximately 95% and the reduction in COD was roughly 88%. From the studies conducted to examine the efficiency of coagulation-flocculation for the removal of surfactants, it was noted that adsorptive micellar flocculation mechanism seems to contribute to the removal of surfactants and organic matters. In the studies carried out by Kaleta et al. [14], the addition of cationic polyelectrolytes appeared to be effective for the coagulation of anionic surfactants, which resulted in a reduction of coagulant

dose. Alternative methods for coagulation have been studied using electrochemical coagulation with  $\text{Fe}^{2+}$  from a soluble anode [9, 16, 17]. In this case, the polarity of the reactor played an important role for the effective removal of the surfactant. Their studies concluded that electrochemical coagulation was a promising method for the treatment of surfactant-rich wastewaters.

Coagulation-flocculation also provides a reasonable treatment, and it uses abundant and low cost chemicals. This process is simple and but is not cost-effective. It has been found to separate a number of particles from water, and enhances filtration process. However, this method requires qualified personnel for construction of chambers and dosage of chemicals, as well as system maintenance. It is a very time consuming process. The main disadvantage of this system is that it transfers the toxic compounds into solid phase when sludge is formed. The sludge require disposal after it is collected.



**Fig 2:** Diagram of Coagulation-Flocculation [17]

### *Adsorption*

Adsorption technology is built on the adsorption of contaminants onto the surface of a filter. This method is effective in eliminating certain organics (e.g. unwanted taste and odours, micropollutants), chlorine, fluorine or radon from drinking water or wastewater. Some of the common adsorbents used are silica gel, zeolite and activated carbon. The adsorption efficiency depends on the nature of adsorbents used, the water composition, and operating parameters.

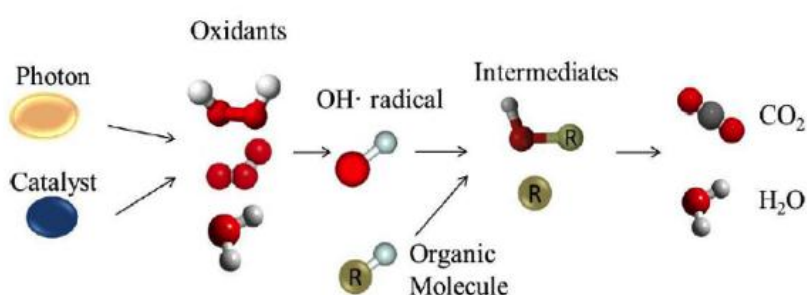
The adsorption of some cationic surfactants was studied previously [7, 18, 19] using various adsorbents such as silica and quartz, zeolite and clinoptilolite, rutile, carbon black and activated carbon. Most investigations conclude that the adsorption mechanism is quite simple and is more effective using small pores. Binds et. al. [20]

determined that at lower surfactant concentrations, adsorption takes place in micropores, whereas more concentration take pace is meso or macropores. They concluded that controlling the pore size distribution of activated carbon would be more beneficial in application using activated carbon for the removal of surfactants from wastewater. In most experiments, they were able to achieve removal efficiency of higher than 98%. The efficiency of adsorption relies on the hydrophobic interaction between the surfactant molecules and the surface of the adsorbent used. Detailed surface chemistry and the oxygen content of the adsorbent considerably influence the adsorption of surfactants.

Activated carbon filters are fairly easy to install, however they need energy and skilled labor and can have high costs due to regular replacement of the filter material. Furthermore, as in the case with most physico-chemical treatment techniques, contaminants are only separated from the wastewater but not destroyed.

### **Chemical Oxidation**

AOP is a process that uses high-energy oxidants, such as ozone or hydrogen peroxide, to generate highly reactive intermediates known as hydroxyl radicals ( $\text{HO}\cdot$ ). It is this  $\text{HO}\cdot$  radical that acts with high efficiency to destroy the organic compounds. The hydroxyl radical is a non-selective powerful chemical oxidant, and once generated attacks almost all organic compounds. Therefore, attack by hydroxyl radicals leads to mineralization of the organic compound, and as a result, AOPs reduce organic contaminants concentration from several hundred ppm to less than 5ppb [26]. In advanced oxidation processes, the hydroxyl radical extracts a hydrogen atom from an organic compound ( $\text{R-H}$ ), and generates an organic radical ( $\cdot\text{R}$ ), which then undergoes a series of chemical transformations to form various oxidation products and by-products [30] as shown in Figure 3.



**Fig 3:** Degradation of an organic compound using AOP

The concept of AOP comprises of the production of hydroxyl radicals in appropriate quantity so as to affect the degradation process [31]. Oxidants that are usually used are hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), Fenton's reagent ( $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ ) and ozone ( $\text{O}_3$ ). Similarly, the processes using a mixture of these oxidants, as well as ultraviolet (UV) irradiation, such as  $\text{H}_2\text{O}_2/\text{UV}$ , ozone/UV, ozone/ $\text{H}_2\text{O}_2/\text{UV}$ , and  $\text{TiO}_2/\text{UV}$  forming hydroxyl radicals ( $\text{HO}\cdot$ ) determine the different methods that are implemented for AOP. Processes that use UV radiation, are known as photochemical processes. The UV radiation acts as a source of energy to activate and enhance the production of hydroxyl radicals. AOPs offer different possible ways for hydroxyl and other radical production. Table 1, summaries the different AOP technologies, and the reactive species produced for the degradation of organic pollutants.

There are numerous studies that have been conducted to investigate the application of advanced oxidation processes for the degradation of recalcitrant surfactants during the past fifteen years. AOPs have gained attention as they lead the way to nullify persistent organic compounds found in wastewater.

**TABLE 1**  
REACTIVE SPECIES FOR DIFFERENT AOPS

AOP	Reactive species
Ozone treatment: $\text{O}_3$	$\cdot\text{OH}$ , $\text{HO}_2\cdot$ , $\text{HO}_3\cdot$ , $\text{O}_2^{\cdot-}$ , $\text{O}_3^{\cdot-}$
$\text{O}_3/\text{H}_2\text{O}_2$	$\cdot\text{OH}$ , $\text{O}_2^{\cdot-}$ , $\text{O}_3^{\cdot-}$
Fenton processes: $\text{H}_2\text{O}_2/\text{Fe}^{2+}$	$\cdot\text{OH}$ , $\text{HO}_2\cdot$
Photo-Fenton processes	$\cdot\text{OH}$
UV/ $\text{O}_3$ , UV/ $\text{H}_2\text{O}_2$ and UV/ $\text{O}_3/\text{H}_2\text{O}_2$	$\cdot\text{OH}$ , $\text{HO}_2\cdot/\text{O}_2^{\cdot-}$ , $\text{O}_3^{\cdot-}$
V-UV ( $\lambda < 190 \text{ nm}$ )	$\cdot\text{OH}$ , $\text{H}^+$ , $\text{e}^-_{\text{aq}}$
Photocatalytic treatment: UV/Vis light using $\text{TiO}_2$ , ZnO, etc. as catalysts	$\cdot\text{OH}$ , $\text{h}^+$ , $\text{O}_2^{\cdot-}$ , $\text{e}^-$ , $^1\text{O}_2$ , $\text{HO}_2\cdot$ , $\text{HOO}\cdot$
Ultrasonic treatment	$\cdot\text{OH}$ , $\cdot\text{H}$
$\gamma$ -Radiolysis	$\cdot\text{OH}$ , $\cdot\text{H}$ , $\text{e}^-_{\text{aq}}$

Fenton process was studied for the removal of two types of surfactants, linear alkylbenzene sulfonates (LAS) and alkyl benzene sulfonate (ABS) [23, 28, 30]. This method was found to work better in acidic solutions, thus requiring maintenance of pH throughout the process. The optimum pH for a number of experiments has been approximately found to be 3. The studies have indicated that it is important to find the optimum amount of  $\text{H}_2\text{O}_2$  for this process, because excess  $\text{H}_2\text{O}_2$  reacts with other inorganic substances in the wastewater, therefore affecting the COD reduction. The findings showed that this process has removal efficiencies exceeding 95% for the degradation of LAS and ABS surfactants and that the type of anionic surfactants had no significant effect on the Fenton oxidation process. Chitra et. al [30] found that the



use of UV radiation source enhanced the rate of degradation of surfactants by 23 times. This is because the UV source enhanced the reduction of  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$ , which reacted with the  $\text{H}_2\text{O}_2$  to generate more hydroxyl radicals. Nevertheless, the drawback of using Fenton's method is the formation of sludge containing iron hydroxide as a byproduct. Therefore, the sludge disposal has to be taken into account for the design and cost assessments when using this process.

In studies carried out for laundry wastewater using ozonation in combination with UV radiation showed that with a high pressure UV lamp, and the amount of initially present dissolved ozone concentration were required to reach the optimum reaction conditions [28, 29, 31-33]. It was concluded that higher temperatures of approximately  $40^\circ\text{C}$  did not improve the treatment efficiency for this process. It was noted that the TOC that originated from the surfactants was removed effectively. However, for this type of AOP, it has been found that there is a high potential for formation of bromate as a byproduct. Researchers have determined that this method uses high amounts of energy in the generation of ozone. Treatment of surfactants with ozone seems to be difficult to implement in the large scale, because this method has been found to be more efficient at lower flowrates. Furthermore, this AOP method will require ozone off-gas treatment which will also increase the costs of operation.

Many organic substrates have been shown to be degraded by photocatalysis with  $\text{TiO}_2$  nanoparticles by which they undergo complete mineralization.  $\text{TiO}_2$  nanoparticles are considered suitable as they are biologically and chemically inert, non-toxic, and affordable and they have a comparatively high oxidative power.  $\text{TiO}_2$  is a readily available material, and the photogenerated holes that are formed are highly oxidizing.  $\text{TiO}_2$  acts as a catalyst in the AOP process for the degradation of surfactants. In the study of the degradation of non-ionic surfactant using this method, complete degradation was found to take place at acidic to base range of pH, with the best degradation was noted to take place at neutral pH conditions [33]. However, for this process, recovery of  $\text{TiO}_2$  is cumbersome and expensive. It was also observed that with time there will be erosion of  $\text{TiO}_2$  used, and this will have to be replaced from time to time. The key advantages of this process are that the operations can be carried out at ambient conditions, and there are no mass transfer limitations when nanoparticles are used as photocatalysts. This process has only been tested in the experimental phase and does not have any large-scale industrial processes yet.

Degradation of LAS has been studied using UV/ $\text{H}_2\text{O}_2$  process [24, 28]. Very high concentration of a LAS mixture was treated with various oxidants ( $\text{H}_2\text{O}_2$ ) to surfactant molar ratios with a low-pressure UV lamp emitting monochromatic radiation at 254 nm with a power output of 8W/L in a recirculated batch reactor [28]. It was found that increasing  $\text{H}_2\text{O}_2$  concentrations improved the LAS removal efficiency, but only up to a certain point. The major factors affecting this process are the initial concentration of the target compound, the amount of  $\text{H}_2\text{O}_2$  used, wastewater pH, presence of bicarbonate and reaction time. Unlike the ozone AOP methods, there are no mass transfer limitations as hydrogen peroxide is soluble in water. This method does not require any off-gas treatment operations. To ensure that there is no hydrogen peroxide in the effluent stream, it is important to optimize and determine the correct

amount of  $H_2O_2$  dosing to ensure that all of it is used in the degradation process. Above optimum concentration of  $H_2O_2$ , the hydrogen peroxide reacts with other contaminants (e.g. elemental sulfur) producing complex oxidizable materials. This is confirmed by the results for the Removal of COD increasing up to a certain point, then decreasing in efficiency. This is the indication that excess peroxide is reacting with other non-organic species. Beyond the optimum time, the efficiency of the system was reduced in the removal of LAS. This may be due to formation of side product resulting from the degradation process with  $H_2O_2$ . Unlike all the other processes, this method is relatively simple and cost effective. UV/ $H_2O_2$  treatment systems are used in large scale for the treatment of drinking water due to its simplicity in operations as well as the equipment required.

#### **IV. CONCLUSION**

It is evident to conclude that when comparing conventional treatment technologies to advanced oxidation processes, there are a few important differences. First and most importantly, when using conventional wastewater treatment technologies, the surfactants are removed from the water but transferred to a different medium (membrane filters, adsorbents, etc.). However, AOPs offer a method to completely destroy the surfactant molecules by breaking them down into smaller fragments. Secondly, conventional methods are time consuming and are easily influenced by changes in season or influent compositions. In case AOPs, the process is optimized for the degradation of specific compounds. Conventional methods are time consuming and require trained personnel to maintain the day to day running of the operations, however AOPs offer faster option for removal of organic pollutants, and most processes are easy to operate and have low maintenance costs. Finally, conventional methods require special hazardous waste handling and disposal for the sludge, filters and adsorbents used or produced during the treatment process. However, AOPs do not produce harmful byproducts, thus do not require special handling or post-treatment technologies. Therefore, it is quite clear that AOPs are a better option for the degradation of surfactants.

Based on the reviews of the different advanced oxidation processes, UV/ $H_2O_2$  has shown the most potential for the degradation of surfactants at lower costs of treatment. Advanced oxidation methods showed over 98% surfactant removal and more than 95% reduction in COD can be achieved. However, all AOPs are compound specific and require process optimization in order to run effectively and efficiently. Some of the studies conducted suggest the combination of AOPs with conventional physico-chemical processes for operations at lower costs. Photo-Fenton process as well as photocatalysis with  $TiO_2$  are also promising options for the degradation of surfactants. It is also crucial to understand the degradation pathway, mechanism and kinetics in order to optimize the process to achieve maximum amount of surfactant removal, as well as reduction in COD and TOC values. It is important to also determine the formation of byproducts, and conduct toxicity tests to ensure that any byproducts formed are not more harmful than the surfactant itself.

AOPs are considered a highly competitive water treatment technology for the removal of organic pollutants not treatable by conventional methods. In order to achieve complete mineralization, AOP alone may prove to be an expensive technique. It has been widely reported that AOP in combination with conventional treatment methods can reduce operating costs.

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## **REFERENCES**

- [1] Ikehata, K., & El-Din, M. G. (2004). "Degradation of recalcitrant surfactants in wastewater by ozonation and advanced oxidation processes: a review". *Ozone: science & engineering*, 26(4), 327-343.
- [2] Tadros, T. 2006. "Surfactants". *Kirk-Othmer Encyclopedia of Chemical Technology*.
- [3] Scott, M. J., & Jones, M. N. (2000). "The biodegradation of surfactants in the environment". *Biochimica et Biophysica Acta (BBA)-Biomembranes*, 1508(1), 235-251.
- [4] Salager, J.L. (1999). "Surfactant – Types and Uses". FIRP BOOKLET # E300-A. Retrieved from <http://nanoparticles.org/pdf/Salager-E300A.pdf>
- [5] Scramm, L.L. (2000). "Surfactants: Fundamentals and Applications in the Petroleum Industry". Cambridge University Press. p. 3
- [6] Adak, A., Bandyopadhyay, M., & Pal, A. (2005). "Removal of anionic surfactant from wastewater by alumina: a case study". *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 254(1), 165-171.
- [7] Ying, G. G. (2006). "Fate, behavior and effects of surfactants and their degradation products in the environment". *Environment international*, 32(3), 417-431.
- [8] Sandeep Kumar Tripathi , Rashmi Tyagi & Barun Kumar Nandi (2013) "Removal of Residual Surfactants from Laundry Wastewater: A Review", *Journal of Dispersion Science and Technology*, 34:11, 1526-1534
- [9] Ge, J., Qu, J., Lei, P., and Liu, H. (2004) *Separation and Purification Technology*, 36: 33–39
- [10] Kowalska, I. (2008) *Desalination*, 221: 351–357

- [11] Christa Korzenowski , Miguel B.O. Martins , Andréa Moura Bernardes , Jane Zoppas Ferreira , Elizabeth C.N.F. Duarte & Maria Norberta De Pinho (2012) “Removal of anionic surfactants by nanofiltration”, *Desalination and Water Treatment*, 44:1-3, 269-275
- [12] Aboulhassan, M A. Souabi, S. Yaacoubi, A. Baudu, M. 2006. “Removal of surfactant from industrial wastewaters by coagulation flocculation process”. *Int. J. Environ. Sci. Tech*, 3, 327-332
- [13] Zhao, P., Gao, B., Yue, Q., & Shon, H. K. (2015). The performance of forward osmosis process in treating the surfactant wastewater: The rejection of surfactant, water flux and physical cleaning effectiveness. *Chemical Engineering Journal*, 281, 688-695.
- [14] Kaleta J Elektorowicz M. 2012. “The removal of anionic surfactants from water in coagulation process”. *Environmental Technology*
- [15] Önder, E., Koparal, A. S., & Ögütveren, Ü. B. (2007). An alternative method for the removal of surfactants from water: Electrochemical coagulation. *Separation and Purification Technology*, 52(3), 527-532.
- [16] Félicien M. (2003). Coagulation-Flocculation Process. Sustainable Sanitation and Water Management. Retrieved from: <http://www.sswm.info/>
- [17] Shang, X., Kim, H. C., Huang, J. H., & Dempsey, B. A. (2015). Coagulation strategies to decrease fouling and increase critical flux and contaminant removal in microfiltration of laundry wastewater. *Separation and Purification Technology*, 147, 44-50.
- [18] Duman, O., & Ayranci, E. (2010). Adsorptive removal of cationic surfactants from aqueous solutions onto high-area activated carbon cloth monitored by in situ UV spectroscopy. *Journal of hazardous materials*, 174(1), 359-367.
- [19] Khan, M.N. and Zareen, U. (2006). “Removal of Surfactants using Adsorption by Granite Sand”. *Journal of Hazardous Materials B*, 133: 269–275
- [20] Bindes, M. M., & Franco Jr, M. R. (2014). Surfactant removal from aqueous solutions onto activated carbon using UV spectroscopy. *Desalination and Water Treatment*, (ahead-of-print), 1-6.
- [21] Kommineni, S., Zoeckler, J., Stocking, A., Liang, P. S., Flores, A., Rodriguez, R., Tom Browne, Roberts, PE R., & Brown, A. “3.0 Advanced Oxidation Processes”. Center for Groundwater Restoration and Protection National Water Research Institute
- [22] Lin, S. H., & Leu, H. G. (1999). “Operating characteristics and kinetic studies of surfactant wastewater treatment by Fenton oxidation”. *Water Research*, 33(7), 1735-1741.
- [23] Paphane, B. D., & Ramirez, L. L. (2013). ‘Chemical Pre-Treatment of Anionic Surfactants Contaminated Waste Water at Enaspol AS using H<sub>2</sub>O<sub>2</sub>/UV Light

- Waste Water Pre-Treatment Method'. *J Environ Anal Toxicol*, 3(181), 2161-0525.
- [24] Stasinakis, A. S. 2008. 'Use of Selected Advanced Oxidation Processes (AOPs) for Wastewater Treatment – A Mini Review'. *Global NEST Journal*, Vol 10, No 3, pp 376-385
- [25] Mohajerani, M. Mehrvar, M. Ein-Mozaffari, F. "An Overview Of The Integration Of Advanced Oxidation Technologies And Other Processes For Water And Wastewater Treatment". *International Journal of Engineering (IJE)*. 2009. Volume (3) : Issue (2), 120 – 146
- [26] Munter, R. "Advanced Oxidation Processes – Current Status And Prospects". *Proc. Estonian Acad. Sci. Chem.*, 2001, 50, 2, 59–80
- [27] Ivanković T, Hrenović J. "Surfactants In The Environment". *Arh Hig Rada Toksikol* 2010;61:95-110
- [28] Bokare, A. D., & Choi, W. (2014). "Review of iron-free Fenton-like systems for activating H<sub>2</sub>O<sub>2</sub> in advanced oxidation processes". *Journal of hazardous materials*, 275, 121-135.
- [29] Al-Sarawy, A. A., & Wali, F. K. M. "Overview on Chemical Oxidation Technology in Wastewater Treatment". Ninth International Water Technology Conference, IWTC9 2005, Sharm El-Sheikh, Egypt.
- [30] Chitra, S., Paramasivan, K., Shanmugamani, A. G., Rao, S. V. S., & Paul, B. (2014). Advanced oxidation processes for the treatment of surfactant wastes. *J Chem Eng Chem Res*, 1, 163-173.
- [31] Eng, Y. Y., Sharma, V. K., & Ray, A. K. (2010). Photocatalytic degradation of nonionic surfactant, Brij 35 in aqueous TiO<sub>2</sub> suspensions. *Chemosphere*, 79(2), 205-209.
- [32] da Silva, S. W., Klauck, C. R., Siqueira, M. A., & Bernardes, A. M. (2015). Degradation of the commercial surfactant nonylphenol ethoxylate by advanced oxidation processes. *Journal of hazardous materials*, 282, 241-248.
- [33] Olmez-Hanci, T., Arslan-Alaton, I., Dursun, D., Genc, B., Mita, D. G., Guida, M., & Mita, L. (2015). Degradation and toxicity assessment of the nonionic surfactant Triton™ X-45 by the peroxymonosulfate/UV-C process. *Photochemical & Photobiological Sciences*, 14(3), 569-575.

