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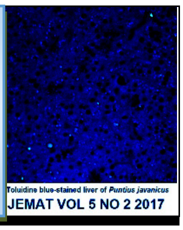

Biodegradation of Sodium Dodecyl Sulfate: A Mini review

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ABSTRACT

Sodium dodecyl sulphate (SDS) is an anionic surfactant that is mostly used in cleaning detergents and commercial products. Its toxicity and pollution in the environment are well documented. In recent years, the use of SDS-degrading bacteria for the purpose of bioremediation of this pollutant has increased several folds. The number of SDS-degrading microorganism are increasingly reported indicating the seriousness of researchers to embark on process and systems for SDS remediation. Despite these efforts, several aspects that still need to be settled are the mechanism of SDS utilization by microorganisms, kinetics of degradation and growth on SDS, the fate and toxicity of degraded and undegraded metabolites, and the potential of using these microorganisms in actual field work. These issues are going to hinder the successful `development of efficient systems for SDS remediation in water bodies and soils.

INTRODUCTION

Sodium dodecyl sulphate (SDS) is an anionic surfactant that is mostly used in cleaning detergents and commercial products. Its toxicity and pollution in the environment are well documented. Studies have revealed that the biodegradation process by using bacteria can control the level of SDS released to the environment [1,2]. Anionic surfactants are most widely used mainly due to good detergency at low temperatures in neutral solutions. They produce negatively charged ions in aqueous solution, originated from sulphate or sulphonate groups. Anionic surfactants have either ester sulphate or sulfonated groups from xenobiotic compounds are widely used in many industrial applications [3–13]. They are an important group of organic substances in SML as they possess a higher solubility of organic and inorganic substances.

The main source of naturally occurring surfactants comes from phytoplankton exudates in sub-surface water (SSW) [14]. Anionic surfactants consist of hydrophilic and hydrophobic parts that readily interact with apolar and polar substructures in macromolecules or else apolar and polar molecules in compound mixtures. Therefore, anionic surfactants can contribute advantages in various heterogeneous phases in many biological systems and technological processes by reducing the energy of interaction and solvation energy [15]. Hydrophilic and hydrophobic parts of anionic surfactants cause accumulation at the interfaces between oil and water or air and water and also lowering the surface tension. Surfactants can be classified into non-ionic, anionic, cationic or amphoteric based on their charge in aqueous solutions. Anionic surfactants are popular additives because of their economic cost and wider applications in industry [5,7,16–24]. In commercial detergents, high number of surfactants are used specifically from anionic surfactants. Anionic surfactants are vital in term of commerce for almost half of the market share of surfactant production. They exist in many aquatic ecosystems due to the high efficiency of wastewater treatment plants to eliminate them and high biodegradability of active surface substances [25].

The waste of this surfactant discharged into fresh water and can harm the environment if the effluents are not treated through the wastewater treatment process. The common anionic surfactants group of aliphatic alkyl sulfatase is sodium dodecyl sulphate (SDS). The applications of SDS are most popular as an anionic surfactant in commercial products used for cosmetics and personal hygiene [26]. Yoslim *et al.* stated that the rate of natural gas hydrate formation is elevated with the presence of anionic surfactants compared to non-ionic and cationic surfactants. Instead of using SDS to enhance the rate of natural gas hydrate formation, it is also best surfactant in order to increase rate difluoromethane (HFC-32) hydrate formation and the water to hydrate conversion [27]. Linear alkylbenzene sulfonates (LASs) which have alkyl chains from C10 to C14 are the most abundant anionic surfactants used in surface cleaners and household detergents.

The second most abundant surfactants which have 12 and 16 carbon units alkyl chain length and an average of a chain of 3 or 4 ethylene oxide (EO) units are alkyl ethoxy sulphates (AES) [28]. Anionic surfactants undergo adsorption to alter the surface characteristics and improve the solubility of sparingly soluble compounds in water. Besides, the resistance to mass transfer can also be transferred. The presence of anionic surfactants in monomeric form is at a low concentration between both polar and apolar solvents. Anionic surfactants can be a factor of toxicity because of contributing toxic symptoms in organs and animal and human organisms due to altering the structure of the protein and also enzyme and phospholipid membranes misfunctioning. They also can give potential to eye and skin irritation besides damage human skin [15].

Effects of surfactants on the environment

With the development of the industrial economy and population increase, large amounts of surfactants are consumed resulting in serious environmental pollution problem. Surfactants, either ionic or non-ionic, are dumped into water reservoirs as sewage by a number of factories and also to soils. Chaturvedi and Kumar reported that higher SDS in the environment is due to its usage in industrial effluents and complex domestic that end up in wastewater flow directly from few applications such as pesticides and oil dispersants[29].

Anionic surfactants have higher proportion and widely used in various applications in industry. Because of large consumption of anionic surfactants, a lot of contaminants are discarded into water bodies and soils. Linear alkyl benzene sulfonated (LAS) is one of the mostly used xenobiotic anionic surfactants and discharged the residues of contaminants in the high amount especially during sewage treatment. It affects the soils that are accumulated with this surfactant and lead to pollution [30]. The major environmental problem arises from semiconductor industries that flow organic and inorganic pollutants into water bodies at high levels, for instance, ammonia, fluoride and SDS [31]. The presence of SDS in environment mainly comes from industrial and domestic wastes, so it is a must to remove this surfactant from the environment to make sure our nature is safer [32].

Water

Excessive use of surfactants mainly sources from detergents become a problematic and serious issue that needs much attention to decrease their pollution focusing on wastewater contamination. Groundwater can be contaminated by surfactants due to percolating process from industrial and municipal sewage systems. In addition, domestic and industrial effluents from unwanted cleaning products also can contribute to groundwater contamination [33]. According to Li *et al.*, contamination of wastewater decreased the oxygenation potentials and caused toxic to waterborne organisms [34]. Furthermore, it can lead to waterborne disease that can harm human's health.

Organism living and drinking water supplies are affected when SDS enters aquatic environments due to its presence in wash water as wastewater or by-product of production processes or simply as a result of normal use and disposal. The remaining surfactants mingle in sediments after rapid degradation in water because of higher affinity of surfactants for organic carbon in specific phase [35]. Toxicity of surfactants might affect mostly on aquatic organisms, but for human, surfactants are not really toxic. For example, surfactants may destroy the chlorophyll-protein in aquatic plants and lengthen their growth and metabolism period. Anionic surfactants will be emitted from the water bodies after they reach a rigid limit which is around 1.0 mg L^{-1} [31]. High amounts of surfactants can cause complications that are clearly seen during the treatment process in sewage treatment plants.

Biological processes and physicochemical level applied in the purification of water are influenced by the presence of detergents in wastewater. During the physicochemical level, the surface tension of the liquid is decreased, lead to the downturn of small particles in sedimentation and flocculation stage. Their deterioration is upon their colloidal suspension stability. The function of sludge microbial collusion is affected on the biological level because of the presence of anionic surfactants. It leads to harm to the biodiversity and responsible for most xenobiotics decomposition [36].

Soil

Soil contamination becomes a critical issue and needs global awareness to solve the problem. It is now considered as a major obstacle to having sustainable development. It damages the ecosystem balance that leads to higher economic loss and harms the human health. Soil contamination problems arise from the poor management of disposal measures, for instance, improper waste disposal and mining tailings. It involves heavy metals and toxic organics that are believed to be a major source of soil contamination [37].

Soils contamination caused by organic pollutant has become a worldwide issue as it contributes a very critical problem to the environment. It is essential to study the pollutants adsorption on soils to ensure the behaviour of pollutants in the soil environment is well-understood. Surfactants enter the soils and adsorb on soils, influence the biological and physicochemical properties of soils. Studies have reported that surfactants affect the hydraulic conductivity of soils, soil water retention, stability of soil aggregates and also metabolism of microbes in soils. The adsorption, mobility and degradation of other organic substances may also be affected by surfactants because of the correlation between organic carbon content of soils and adsorption of surfactants [38]. Cserhati *et al.* reported that the hydraulic conductivity of soil is reduced when SDS is added to the soils. The effect is influenced by the clay content of the soil and also SDS concentration. That study revealed that the twin head group of anionic surfactants are less susceptible to adsorption and precipitation to soil particle[15].

Sodium Dodecyl Sulphate (SDS)

Properties of SDS

Sodium dodecyl sulphate (SDS) can be also known in the other name which is Sodium Lauryl Sulphate (SLS). It is derived from alcohol sulfates, and it is one of the alcohol detergents. The molecular formula for SDS is $C_{12}H_{25}NaO_4S$ while its molecular weight is 288.38 g mol^{-1} [39]. Sodium dodecyl sulphate (SDS) which is an anionic surfactant is an essential component of various surfactant formulations. It has been used extensively in household products and commercial products used for personal hygiene and cosmetics due to its low cost and excellent foaming properties. The molecule of SDS (**Fig. 1**) has 12 carbon atoms attached to a sulphate group giving it amphiphilic properties that are required for a detergent [40]. Sodium dodecyl sulphate (SDS) can be classified by the structure of linear long chain sulphate ester. This structure will undergo desulfation and then assimilation during the degradation by a few bacterial strains [30].

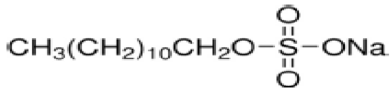

Fig. 1. Structure of sodium dodecyl sulphate (SDS) [41].

Sodium dodecyl sulphate is very commonly used in industry as a penetrant, de-inking agent, flocculating agent in pulp and paper industry; additive of concrete in building construction as well as the wool cleaning agent and leather softening agent. SDS is being proved as an excellent chemical absorbent. It has an important role in increasing the intestinal absorption of poor drug absorbent through trans-epidermal, nasal and ocular drug delivery systems. Currently, SDS is widely used for electrophoresis method in biochemical research [29]. Sulphate may be produced from the surfactant sodium dodecyl sulphate (SDS), and it is believed to harm the environment due to highly toxic properties at higher [42].

The surfactant toxicity is indicated by the length of the hydrocarbon alkyl chain, which has the bulky chemical structure [43]. When the surfactants have a higher number of chains for each group, the antimicrobial activity of the surfactants will be higher. Besides, this surfactant has a greater tendency in micelles formation when it has longer surfactant chains. Surfactant interaction with the active sites located on the cellular membrane will face decrement due to micelle formation. However, the level of toxicity is independent of the length chain of surfactants. During the study, SLES and SDS were compared, and the result showed the SDS has higher toxicity rather than SLES in the same organism tested although both of them have a same number of carbon alkyl chains which is C12 [43].

Long chain aliphatic sulphate ester which is sodium dodecyl sulphate (SDS), is being used widely in surfactant formulations because of its excellent ability in cleansing. In every pond or water body during the study, the SDS-degrading bacteria are present to prove the biodegradability of this detergent [44]. Although the membrane is a primary target structure, biochemical and physical of cells are affected by sodium dodecyl sulphate (SDS). It will lead to differentiation in vitro and also epidermal cell proliferation. If compared with human, SDS is more harmful to animals as reported that SDS may cause hyperplasia and skin irritation in guinea pigs. In addition, SDS is more sensitive to rabbit skin cultures. The oral route in mammals by SDS is not convenient [39].

Sodium dodecyl sulphate (SDS) gives bad effects towards individual health if the consumption is ≤150 g and can lead to death. Besides, SDS for about ≤20% can cause skin irritation and inflammation if it is directly contacted with skin. Dermatitis can be induced if SDS is exposed repeatedly. SDS is also had the reactive property that can cause individuals might facing difficulty in breathing and lung damage [39].

Applications of SDS

Sodium dodecyl sulphate (SDS) is important in various industries for examples, the industry of textiles, paints and paper [45]. Buffered solutions (BHF) are commonly used in the semiconductor industry during the process of cleaning and etching of silicon wafers. This solution needs the combination of different proportions HF and NH_4F, so in order to minimize particles adhesion on the water surface, SDS is added to the acidic solutions. However, the application of SDS in the industry may generate toxic waste at a higher level [31]. Sodium dodecyl sulphate (SDS) can undergo extraction or soil washing in order to eliminate organic matter. Hence, water and soil can be remediated by SDS that acts as an auxiliary agent [42]. Sodium dodecyl sulphate (SDS) has an excellent biocidal activity which can destroy the bacteria and fungi when in contact with water in a water treatment plant. It is also a powerful tool to be used in disinfection purpose [46]. Anionic surfactants bind to the enzyme in order to give effect to enzyme activities. ATPase activity of P-glycoprotein is inhibited by SDS at low concentrations [15].

SDS is able to restrain some nitrogen-fixing cyanobacteria growth because it possesses bactericidal properties [36].Crop performance can be improved when it is under stress due to the presence of SDS in the genetic engineering field [39]. Besides, SDS can wash out heavy metals with the higher CMC of SDS. Heavy metals can be bind by SDS due to sulphur-containing groups in its molecules [37]. Detergents which contain SDS can avoid from flocculation because SDS acts as a dispersant agent [41].

Toxicity of SDS

Large consumption of Sodium Dodecyl Sulphate (SDS) in the world together with its adverse effects on living organisms makes this surfactant one of the major environmental concerns. Possible toxic effects of SDS have been studied by many researchers. According to Cserhato et al., [13,47–51], the levels of toxicity increases when the length of the alkyl chain increases within the different classes of surfactants. Studies have revealed that SDS is toxic to aquatic animals such as fish, microbes like yeasts and bacteria and also to mammals [44,52]. According to Gibson *et al.*, SDS also can cause deformities of aquatic organisms and can be fatal in acute exposure. Four molluscs species have been tested for acute toxicity of SDS with different concentrations of SDS. As a result, molluscs species with the higher concentration of SDS recorded a higher number of deaths [33].

SDS is commonly used in toxicity test as a reference due to its consistent toxicity, fast acting and non-selective. In SDS acute toxicity testing, invertebrates are more sensitive compared to fish and molluscs species [33]. Icgen *et al.* stated that higher residual surfactants than their critical micelle concentrations present in subsurface environments or water surface result in an increment of ecotoxicological effects[26]. DO concentrations can indicate the level toxicity of surfactants. Higher concentration of DO will decrease the surfactant toxicity [43]. The anionic surfactant which is SDS can give carbon source to bacteria and at the same time bacteria can degrade SDS although SDS give toxic effects when its concentration out of range. SDS concentrations around 0.0025±300 mg L^{-1} is harmful because of its toxicity [45,53]. SDS also can affect the aquatic animals, microbes and also humans that are involved in consuming water contaminated with detergents [46]. Important remediation of SDS in the environment is bioremediation, which is more economical and effective than physiochemical methods in many instances [54].

Bioremediation

Bioremediation can be described as a process of eliminating environmental contaminants that involve microbes, plants or enzymes from microbes or plants. It may also be defined as the destruction of chemical compounds by the biological action of living organisms. Biological agents mainly microorganisms such as bacteria and fungus are usually applied in bioremediation in order to clean up the contaminated environment [2] due to cost-effective, more safer and compatible [1,26,55,56]. Bioremediation exploits microorganisms which have pollutant-degrading capabilities to convert the toxic pollutants to become less toxic or non-toxic compounds. There are two major classifications of bioremediation which are *in situ* and *ex-situ* techniques. *In situ* bioremediation is a process of remediating contaminants at the site and thus, the microbes may accelerate the natural biodegradation in a contaminated area while *ex-situ* bioremediation is a process of treating contaminants after they are removed and excavated which is different from the contaminated area [55].

Bioremediation has become important and gained much attention due to the increased use of SDS [34]. Sodium dodecyl sulphate (SDS) is one of the most famous detergents for anionic surfactant group, and it is a suitable candidate to undergo soil bioremediation [36]. When SDS is discharged to the water surface, the concentration of anionic surfactant disposal into the environment becomes higher. SDS is very toxic and harmful to living organisms, so removing SDS through bioremediation was realized to be an effective method to reduce its toxicity in environments [32]. Better strains that are having optimum growth temperature and fast degradation capacity are on demands to remediate it in order to ensure excellent bioremediation [56]. Jovcic *et al.* mentioned that surfactants must be eliminated rapidly from the environment to evade secondary pollution [57].

Biodegradation of SDS

Soil and aquatic microorganisms are responsible for performing the biodegradation of SDS and the release of carbon dioxide, gas and water. *Pseudomonas sp.* is the efficient bacteria and mostly studied to biodegrade SDS. Alkyl sulfatase is the enzyme that initiates SDS biodegradation by hydrolysing inorganic sulphate with alcohol and then assimilated through the metabolic pathway [40]. The pathway of SDS degradation (**Fig. 2**) is given below;

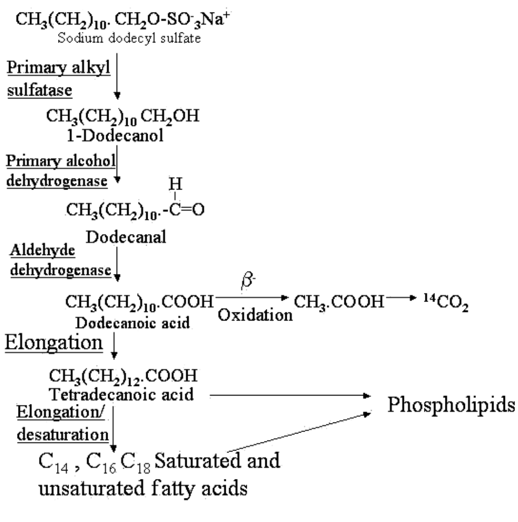

Fig. 2. Metabolic pathway of SDS degradation, from [58].

Biodegradation of SDS is initiated by primary or secondary alkyl sulfatase. Then, liberated primary or secondary alcohols are oxidized by alcohol dehydrogenases. Alkyl sulfatase can be multiplied by the *Pseudomonas* sp. The oxidation of alcohol to acids takes place by alcohol dehydrogenase and then the acids are being utilized as a sole source of carbon and acts as substrates in the β-oxidation pathway [58]. To measure the degradation rate of SDS, it is important to measure the isolates growth and SDS disappearance [44].

SDS-degrading Bacteria

Sodium dodecyl sulphate (SDS) is widely used in cleaning detergent, and the waste of this anionic surfactant is commonly released through water bodies and soils. SDS must be removed from the environment due to its toxicity property that can be lethal to organisms. Thus, bioremediation is suggested by researchers to be an effective method to reduce SDS toxicity [32]. The current strategy for remediation of soils and water bodies polluted with SDS is best carried out using bacteria because of cost-effectiveness.

Better strains are needed when the amount of SDS disposal keep increasing in order to ensure the effectiveness of SDS removal from the environment [56]. Rebello *et al.* reported that SDS degradation is mainly involved in soil or aquatic microorganisms that are predominantly carried out by the *Pseudomonas* species. Pseudomonas genus can be found everywhere, and it is a popular and powerful degrader of toxic compounds including industrial effluents especially sodium dodecyl sulphate (SDS) [59]. Reports have shown that some bacteria that are capable of degrading SDS in the environment have been identified. Some of the examples are shown in **Table 1.**

Table 1. Bacteria that are capable of degrading SDS.

Bacteria	References
Pseudomonas plecoglossicida	[56]
Delftia acidovorans	[52]
Pseudomonas aeruginosa	[45]
Bacillus subtilis and bacillus cereus	[60]
Pseudomonas putida sp3	[44]
Klebsiella oxytoca	[61]
Klebsiella oxytoca istrain af-7	[53]
Bacillus amyloliquefaciens strain kik-12	[62]
Enterobacter sp. strain neni-13	[63]

SDS is utilized by bacteria as the carbon source. Alkyl sulfatase enzyme is responsible for SDS degradation that generates carbon dioxide and water [45]. Rapid removal of surfactants is important to make their application safer, so strains that have the highest percentage of SDS degradation are much needed [61]. An important aspect lacking from the literature is actual bioremediation works involving polluted water bodies or soils. This lacking in information is probably caused by the difficulty in remediating SDS from large water bodies and soils and the fact that SDS is rapidly degraded by indigenous microorganisms. Remediation using isolated microorganisms will be useful in sites where the concentration of SDS is very high and have decimated indigenous microbial population. In this instance, the recovery of indigenous SDS-degrading microorganisms will be slow and the addition of autochthonous SDS-degrading microorganisms at this site will be advantageous. Another important issue that has not been raised much by researchers is the kinetics of growth and degradation on SDS, which is almost non-existent in current body of literature.

Alkyl sulfatase

Sulfatase (EC 3.1.6) belongs to the esterase class that involves the hydrolysis of sulphate esters. Alkyl sulfatase or SdsA sulfatase is one of the members of sulfatases group 3 that can be differentiated with the existence of metallo-β-lactamase domain. Alkyl sulfatase through sdsA gene in *Pseudomonas* sp. ATCC19151 degrades anionic surfactants [57]. Alkyl sulphatase is a powerful tool to conduct future studies in order to make sure the anionic surfactant; SDS is completely eliminated from the environment [40]. Chaturvedi and Kumar reported that alkyl sulfatase is responsible for initiating the degradation of sodium dodecyl sulphate (SDS) which is an anionic surfactant [45]. Alkyl sulfatase is involved in the formation of inorganic sulphate (1-dodecanol) by catalysing hydrolytic cleavage of the ester bond. Alcohol dehydrogenase oxidized 1-dodecanol to 1-dodecanoic acid that is being utilized by the β-oxidation pathway as a carbon source [64].

There are three different groups of alkyl sulfatases that have been reported from *Pseudomonas* sp. which are aryl sulfatases characterized by cysteine or serine active site and specifically from eukaryotes, Fe(ll) α-ketoglutarate-dependent dioxygenase superfamily of sulfatase and alkyl sulfatase enzyme (SdsA) with Zn^{2+} binding [45]. Degradation of anionic surfactants by bacteria is due to the activities of alkyl sulfatase. Bacteria with higher SDS-degrading ability usually have higher alkyl sulfatase activity. During the mid-exponential phase of growth, the activities of alkyl sulfatase in all the isolates were measured. The isolates which have higher activity of alkyl sulfatase are believed to degrade SDS from the polluted areas efficiently and fast [44]. In addition, the involvement of bacteria in alkyl sulfatase ester metabolism shows the bacteria capability to produce a multiple of alkyl sulfatase [44]. Icgen et al. discovered several *Pseudomonas* spp. and one *Aeromonas* sp. bacteria with alkyl sulfatase activity and have attributed a 152 kDa protein band from a zymogram as the dominant protein band with alkyl sulfatase activity [65].

Detection of Anionic Surfactant

Anionic surfactants are discharged into the environment through both domestic and industrial wastewater that causes water pollution of the water-supply source. Therefore, it is vital to control surfactant content on surface water sample by determining the concentration of anionic surfactant. The non-specific method is usually used to measure the concentration of anionic surfactants which is the Methylene Blue Active Substances (MBAS) assay.

The Methylene Blue Active Substances (MBAS) assay (**Fig. 3**) is a spectrophotometric method for determining anionic surfactants, based on the formation of the ionic pair between anionic surfactant and methylene blue [66,67]. The MBAS assay has been long applied as a standard method for determination of surface agents in tap water samples (ISO 7875-1, 1996). Patrao *et al.* reported that the MBAS assay is also used for indication of anionic surfactant degradation by observing the remaining dye in the chloroform layer. It has been used for anionic surfactant determination due to rapid test times, lower equipment cost and portability. In addition, this method is relatively simple and faster than chromatographic techniques [60].

However, it requires a large amount of sample and chloroform as well as very tedious. Because of this limitation, some researchers proposed simplification method for this assay. This was done by using chromatomembrane cell or decreasing the volume of the reagent and sample used [66,67]. Wyrwas and Zgoła-Grzes´kowiak stated that the highest priorities for monitoring purposes are fast, cheap and relatively simple methods [67].

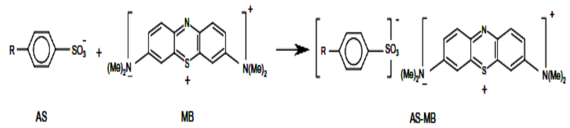

Fig. 3. Anionic surfactant-methylene blue (AS-MB) aggregates [66].

CONCLUSION

Sodium Dodecyl Sulphate (SDS) is very toxic to all organisms. Frequently, SDS is present in water bodies and soils and is very difficult to be removed through physicochemical methods as SDS adsorbs to soil particles. The best way is through bioremediation. However, the partial purification of alkyl sulfatase from SDS-degrading bacterium is very important before a full fledge purification of the enzyme is carried out in the future. The purification and characterization of alkyl sulfatase from detergent-degrading bacterium are very important for understanding the mechanism of degradation of SDS. In addition, the results are important for future improvement of degradation through genetic engineering or strain improvement or even enzyme immobilization. The partial purification and characterization work from this bacterium will provide data for designing a better purification strategy.

ACKNOWLEDGEMENT

REFERENCES

1. Prajapati H, Chauhan P, Gahlout M, Patel B, Patel H. Isolation and characterization of detergent degrading bacteria from soil. Int J Adv Res Biol Sci. 2017;4(4):164–8.
2. Singh S, Gupta VK. Biodegradation and bioremediation of pollutants: perspectives strategies and applications. Int J Pharmacol Bio Sci. 2016;10(1):53–65.
3. Hashim MA, Hassan RS, Kulandai J. Malaysian studies of recalcitrant detergent wastewater. Effl Water Treat J. 1985;25(11):391–3.
4. Matthijs E, De Henau H. Determination of LAS. Determination of linear alkylbenzenesulfonates in aqueous samples, sediments, sludges and soils using HPLC. Tenside Deterg. 1987;24(4):193–199.
5. Vives-Rego J, Vaque MD, Leal JS, Parra J. Surfactants biodegradation in sea water. Tenside Surfactants Deterg. 1987;24(1):20–2.
6. Ludwig HF, Sekaran AS. Evaluation of use of anionic detergents (ABS) in Malaysia. Water Res. 1988;22(2):257–62.
7. Okpokwasili GC, Olisa AO. River-water biodegradation of surfactants in liquid detergents and shampoos. Water Res. 1991;25(11):1425–9.
8. Amund OO, Ilori MO, Odetundun FR. Degradation of commercial detergent products by microbial populations of the Lagos Lagoon. Folia Microbiol (Praha). 1997;42(4):353–6.
9. Junfeng Y, Haowen C, Baoling W, Yongqi L. The anion detergent pollution of Antarctic Maxwell Bay and its adjacent sea areas. China Environ Sci. 1998;18(2):151–3.
10. Singh KL, Kumar A, Kumar A. Short communication: *Bacillus cereus* capable of degrading SDS shows growth with a variety of detergents. World J Microbiol Biotechnol. 1998;14(5):777–9.
11. Pettersson A, Adamsson M, Dave G. Toxicity and detoxification of Swedish detergents and softener products. Chemosphere. 2000;41(10):1611–1620.
12. Ogbulie TE, Ogbulie JN, Umezuruike I. Biodegradation of detergents by aquatic bacterial flora from Otamiri River, Nigeria. Afr J Biotechnol. 2008;7(6):824–30.

13. Rebello S, Asok AK, Mundayoor S, Jisha MS. Surfactants: Toxicity, remediation and green surfactants. Environ Chem Lett. 2014;12(2):275–87.
14. Alsalahi MA, Latif MT, Ali MM, Magam SM, Wahid NBA, Khan MF, et al. Distribution of surfactants along the estuarine area of Selangor River, Malaysia. Mar Pollut Bull. 2014;80(1–2):344–50.
15. Cserháti T, Forgács E, Oros G. Biological activity and environmental impact of anionic surfactants. Environ Int. 2002;28(5):337–48.
16. Falbe J. Surfactants in consumer products: Theory, technology and application. Heidelberg: Springer-Verlag; 1987.
17. Swisher RD. Surfactant biodegradation. Surfactant Sci Ser. 1987;18.
18. Okpokwasili GC, Odokuma LO. Effect of salinity on biodegradation of oil spill dispersants. Waste Manag. 1990;10(2):141–6.
19. Dentel SK, Allen HE, Srinivasarao C, Divincenzo J. Effects of surfactants on sludge dewatering and pollutant fate. Dep Civ Eng Univ Del USA. 1993;
20. White GF, Russell NJ. Biodegradation of anionic surfactants and related molecules. In: Biochemistry of microbial degradation. Springer; 1994. p. 143–177.
21. Renner R. European bans on surfactant trigger transatlantic debate. Environ Sci Technol. 1997;31:316–320.
22. Karsa DR. Coming clean: the world market for surfactants. Chem Ind. 1998;9:685–691.
23. Sales D, Perales JA, Manzano MA, Quiroga JM. Anionic surfactant biodegradation in seawater. Boletin Inst Espanol Oceanogr. 1999;15(1):517–522.
24. Hummel DO. Handbook of surfactant analysis, Chemical, Physico-chemical and Physical Methods. John Willey & Sons Ltd; 2000.
25. Pedraza A, Sicilia MD, Rubio S, Pérez-Bendito D. Assessment of the surfactant-dye binding degree method as an alternative to the methylene blue method for the determination of anionic surfactants in aqueous environmental samples. Anal Chim Acta. 2007;588(2):252–60.
26. Icgen B, Salik SB, Goksu L, Ulusoy H, Yilmaz F. Bioattenuation of detergent plant effluents enhanced via single microbial augmentations. J Surfactants Deterg. 2016;19(3):637–44.
27. Yoslim J, Linga P, Englezos P. Enhanced growth of methane-propane clathrate hydrate crystals with sodium dodecyl sulfate, sodium tetradecyl sulfate, and sodium hexadecyl sulfate surfactants. J Cryst Growth. 2010;313(1):68–80.
28. Gomez V, Ferreres L, Pocurull E, Borrull F. Determination of non-ionic and anionic surfactants in environmental water matrices. Talanta. 2011;84(3):859–66.
29. Chaturvedi V, Kumar A. Isolation of sodium dodecyl sulfate degrading strains from a detergent polluted pond situated in Varanasi city , India. J Cell Mol Biol. 2010;8(2):103–11.
30. Abboud MM, Khleifat KM, Batarseh M, Tarawneh KA, Al-mustafa A, Al-madadhah M. Different optimization conditions required for enhancing the biodegradation of linear alkylbenzosulfonate and sodium dodecyl sulfate surfactants by novel consortium of Acinetobacter calcoaceticus and Pantoea agglomerans. Enzyme Microbe Tech. 2007;41:432–9.
31. Aoudj S, Khelifa A, Drouiche N. Removal of fluoride, SDS, ammonia and turbidity from semiconductor wastewater by combined electrocoagulation-electroflotation. Chemosphere. 2017;180:379–87.
32. Chaturvedi V, Kumar A. Isolation of a strain of *Pseudomonas putida* capable of metabolizing anionic detergent sodium dodecyl sulfate (SDS). Iran J Microbiol. 2011;3(1):47–53.
33. Gibson KJ, Miller JM, Johnson PD, Stewart PM. Toxicity of sodium dodecyl sulfate to federally threatened and petitioned freshwater mollusk species. Freshw Mollusk Biol Conserv. 2016;19:29–35.
34. Li S, Su Y, Liu Y, Sun L, Yu M, Wu Y. Preparation and characterization of cross-linked enzyme aggregates (CLEAs) of recombinant thermostable alkylsulfatase (SdsAP) from Pseudomonas sp. S9. Process Biochem. 2016;51(12):2084–9.
35. Lara-Martín PA, Petrovic M, Gómez-Parra A, Barceló D, González-Mazo E. Presence of surfactants and their degradation intermediates in sediment cores and grabs from the Cadiz Bay area. Environ Pollut. 2006;144(2):483–91.
36. Furmanczyk EM, Kaminski MA, Spolnik G, Sojka M. Isolation and characterization of *Pseudomonas* spp. strains that efficiently decompose sodium dodecyl sulfate. 2017;8(November):1–16.
37. Mao X, Jiang R, Xiao W, Yu J. Use of surfactants for the remediation of contaminated soils : A review. J Hazard Mater. 2015;285:419–35.
38. Rao P, He M. Adsorption of anionic and nonionic surfactant mixtures from synthetic detergents on soils. Chemosphere. 2006;63(7):1214–21.
39. Kumar S, Kirha TJ, Thonger T. Toxicological effects of sodium dodecyl sulfate. 2014;6(5):1488–92.
40. Ambily PS, Jisha MS. Characterization of alkyl sulphate required for the biodegradation of Sodium Dodecyl Sulphate (SDS). Eur J Exp Biol. 2011;1(4):41–9.
41. Ramprasad C, Philip L. Contributions of various processes to the removal of surfactants and personal care products in constructed wetland. Chem Eng J. 2018;334(September 2017):322–33.
42. Araújo KCDF, Barreto JPDP, Cardozo JC, Vieira E, Araújo DM De, Martínez-huitle CA. Sulfate pollution : evidence for electrochemical production of persulfate by oxidizing sulfate released by the surfactant sodium dodecyl sulfate. Environ Chem Lett. 2018;2(0123456789):1–6.
43. Bailey KL, Tilton F, Jansik DP, Ergas SJ, Marshall MJ, Miracle AL, et al. Ecotoxicology and environmental safety growth inhibition and stimulation of Shewanella oneidensis MR-1 by surfactants and calcium polysulfide. Ecotoxicol Environ Saf. 2012;80:195–202.
44. Chaturvedi V, Kumar A. Diversity of culturable sodium dodecyl sulfate (SDS) degrading bacteria isolated from detergent contaminated ponds situated in Varanasi city, India. Int Biodeterior Biodegrad. 2011;65(7):961–71.
45. Chaturvedi V, Kumar A. Presence of SDS-degrading enzyme, alkyl sulfatase (SdsA1) is specific to different strains of Pseudomonas aeruginosa. Process Biochem. 2013;48(4):688–93.
46. Chaturvedi V, Kumar A. Metabolism dependent chemotaxis of *Pseudomonas aeruginosa* N1 towards anionic detergent sodium dodecyl sulfate. 2014;54(June):134–8.
47. Lewis MA. Chronic and sublethal toxicities of surfactants to aquatic animals: A review and risk assessment. Water Res. 1991;25(1):101–13.
48. Scott MJ, Jones MN. The biodegradation of surfactants in the environment. Biochim Biophys Acta - Biomembr. 2000;1508(1–2):235–51.
49. Sirisattha S, Momose Y, Kitagawa E, Iwahashi H. Toxicity of anionic detergents determined by *Saccharomyces cerevisiae* microarray analysis. Water Res. 2004;38(1):61–70.
50. Kumar M, Trivedi SP, Misra A, Sharma S. Histopathological changes in testis of the freshwater fish, *Heteropneustes fossilis* (Bloch) exposed to linear alkyl benzene sulphonate (LAS). J Environ Biol. 2007;28(3):679–84.
51. Chaturvedi V, Kumar A. Isolation of sodium dodecyl sulfate degrading strains from a detergent polluted pond situated in Varanasi city, India. J Cell Mol Biol. 2010;8(2):103–11.
52. Yilmaz F, Icgen B. Characterization of SDS-degrading Delftia acidovorans and in situ monitoring of its temporal succession in SDS-contaminated surface waters. Environ Sci Pollut Res. 2014;21(12):7413–24.
53. Masdor N, Abd Shukor MS, Khan A, Bin Halmi MIE, Abdullah SRS, Shamaan NA, et al. Isolation and characterization of a molybdenum-reducing and SDS- degrading *Klebsiella oxytoca* strain Aft-7 and its bioremediation application in the environment. Biodiversitas. 2015;16(2):238–46.
54. Khayat ME, Rahman MFA, Shukor MS, Ahmad SA, Shamaan NA, Shukor MY. Characterization of a molybdenum-reducing Bacillus sp. strain khayat with the ability to grow on SDS and diesel. Rendiconti Lincei. 2016;27(3):547–56.
55. Rangari NT, Kalyankar TM, Puranik PK, Kalmegh SM, Chaudhari SR. An Overview On: Bioremediation. Int J Pharm Ther. 2012;2(4):746–57.
56. John EM, Rebello S, Asok AK, Jisha MS. *Pseudomonas plecoglossicida* S5, a novel nonpathogenic isolate for sodium dodecyl sulfate degradation. Environ Chem Lett. 2015;13(1):117–23.

57. Jovcic B, Venturi V, Davison J, Topisirovic L, Kojic M. Regulation of the sdsA alkyl sulfatase of *Pseudomonas* sp. ATCC19151 and its involvement in degradation of anionic surfactants. J Appl Microbiol. 2010;109(3):1076–83.
58. Chaturvedi V, Kumar A. Bacterial utilization of sodium dodecyl sulfate. Int J Appl Biol Pharm Technol. 2010;I(3):1126–31.
59. Rebello S, Asok AK, Mundayoor S, Jisha MS. Surfactants: Toxicity, remediation and green surfactants. Environ Chem Lett. 2014;12(2):275–87.
60. Patrao S, Acharya A, Suvarna N, Sequeira M. Degradation of anionic surfactants by *Bacillus subtilis* and *Bacillus cereus*. Pharm Biol Sci. 2012;3(1):42–5.
61. Shukor MY, Husin WSW, Rahman MFA, Shamaan NA, Syed MA. Isolation and characterization of an SDS-degrading Klebsiella oxytoca. J Environ Biol. 2009;30(1):129–34.
62. Maarof MZ, Shukor MY, Mohamad O, Karamba KI, Halmi MIE, Rahman MFA, et al. Isolation and characterization of a molybdenum-reducing *Bacillus amyloliquefaciens* strain KIK-12 in soils from Nigeria with the ability to grow on SDS. J Environ Microbiol Toxicol. 2018;6(1):13–20.
63. Rahman MF, Rusnam M, Gusmanizar N, Masdor NA, Lee CH, Shukor MS, et al. Molybdate-reducing and SDS-degrading *Enterobacter* sp. strain Neni-13. Nova Biotechnol Chim. 2016;15(2):166–181.
64. Shahbazi R, Kasra-kermanshahi R, Gharavi S, Nejad ZM-, Borzooee F. Screening of SDS-degrading bacteria from car wash wastewater and study of the alkylsulfatase enzyme activity. Iran J Microbiol. 2013;5(2):153–8.
65. Icgen B, Salik SB, Goksu L, Ulusoy H, Yilmaz F. Higher alkyl sulfatase activity required by microbial inhabitants to remove anionic surfactants in the contaminated surface waters. Water Sci Technol. 2017;76(9):2357–2366.
66. Jurado E, Fernández-Serrano M, Núñez-Olea J, Luzón G, Lechuga M. Simplified spectrophotometric method using methylene blue for determining anionic surfactants: Applications to the study of primary biodegradation in aerobic screening tests. Chemosphere. 2006;65(2):278–85.
67. Wyrwas B, Zgoła-Grześkowiak A. Continuous flow methylene blue active substances method for the determination of anionic surfactants in river water and biodegradation test samples. J Surfactants Deterg. 2014;17(1):191–8.