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To cite this article: Qi Wu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **227** 052023

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# Research progress of surfactant biodegradation

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**Abstract:** Due to various function in solubilisation, dispersion, emulsification, corrosion inhibition, biocidal properties, lubricity and viscosity modification, surfactants are widely applied in industrial, agricultural, pharmaceutical, food, cosmetic and other fields. Surfactants bring convenience to people, but meanwhile, resulting in the accumulation of numerous of toxic or harmful substances in the environment and causing serious ecological problems, even threatening human health. So it's an urgent problem to be solved to degrade the surfactant in the environment. The biodegradation of surfactants is a highly efficient, safe, environmentally friendly and widely used method. This paper discusses the biodegradation of different surfactants, the mechanism for biodegradation, the factors that affect biodegradation and methods of detecting biodegradability.

## 1. Introduction

Surface active agent (surfactant) is a substance that can change the free energy of the interface at low concentration. It has the effects of solubilization, dispersion and emulsification [1]. In addition, the different compositions of surfactants also endow them with different auxiliary functions, such as anti-corrosion, antibacterial, lubricating, tackifying, etc. Due to its unique properties and diversified functions, surfactants are widely used in industry, agriculture, medicine, food, daily chemical and other fields. At the same time, the extensive use of surfactants has also resulted in the accumulation of toxic or harmful substances in the environment, causing serious ecological problems. Surfactants in water can accumulate in the viscera and gills of fish, causing asphyxiation and death of fish [2]; Surfactants in soil are toxic to microorganisms [3], and can damage roots [4], and inhibit photosynthesis of plants [5]; The use of surfactants can also be harmful to the human body and can cause diseases such as dermatitis and oral ulcers [6, 7]. Therefore, degrading the surfactant in the environment, maintaining the balance of the ecological environment and protecting human health have become important tasks in the process of production and use of surfactants.

In addition to strictly controlling the use of surfactants and regulating the emission treatment of surfactants, the degradation of surfactants already existing in the environment cannot be ignored. The degradation of surfactant is to change the structure of surfactant under the external factors, and to convert the harmful structural components of surfactant into environmentally friendly components. Methods of degrading surfactants include oxidation, electrolysis, photolysis, sonication and biodegradation. Oxidation method is the treatment of wastes containing surfactant by using strong oxides, such as ozone, hydrogen peroxide and ferric salt, so as to make it undergo oxidation-reduction reaction and degrade into non-toxic and harmless substances [8, 9]. The electrolysis method is to mineralize and degrade the surfactants in the waste liquid by using the strong oxidizing substances produced on the surface of the electrodes, such as PbO<sub>2</sub>, BDD and so on, during the electrolysis



process [10]. In addition to the traditional photolysis of UV-excited hydrogen peroxide oxidation surfactant, at present, the commonly used photolysis is to induce the redox reaction of surfactant by using non-toxic and efficient semiconductor  $\text{TiO}_2$  to undergo electron transition under the irradiation of ultraviolet light to achieve the purpose of degradation [11]. Ultrasonic degradation is a method of removing surfactant by ultrasonic cavitation of waste liquid under fairly high sound pressure accompanied by high temperature and high pressure oxidation [12]. Biodegradation is a method of decomposing surfactant into carbon dioxide and water as a carbon source for microbial life metabolism by means of the decomposition of organic substances by microorganisms in the environment. The oxidation method utilizes chemical reagents to carry out oxidation reaction, and the final product is uncontrollable and easy to cause secondary pollution; the photolysis reaction conditions are mild without secondary pollution, but the degradation rate is low; and although the electrolysis method and sonication method have good degradation effect, but they consume a lot of energy. Compared with other methods, biodegradation is a more effective, safer, more environmentally friendly and more widely used degradation method.

The biodegradation of surfactants can be divided into three stages according to various degradation products [13]: (1) Primary degradation: Through microbial degradation, the parent structure of surfactant is changed and its original surface activation characteristics are lost. (2) Secondary degradation: the product obtained by degradation can be completely and rapidly degraded by microorganisms without causing any pollution to the environment; (3) Final degradation: The surfactant is completely degrade, and the final product is water,  $\text{CO}_2$ , mineral salt and other inorganic substances.

## 2. Species and biodegradation of surfactants

The surfactant has a unique molecular structure that makes it amphiphilic: one end is hydrophilic group, such as hydroxyl, carboxyl, amino and other polar groups; the other end is hydrophobic group, also known as lipophilic group, such as alkyl, aryl and other non-polar groups. Surfactants are classified into anionic surfactants, cationic surfactants, nonionic surfactants and amphoteric surfactants according to the dissociation properties of polar groups. The biodegradation of surfactants is mainly determined by hydrophobic groups, and the biodegradability of different types of surfactants is different.

### 2.1. Anionic surfactants

Anionic surfactants can dissociate negatively charged surfactant ions in solution, and are the most commonly used surfactants, which are active in food, pharmaceutical, cosmetic, detergent and other industries [14]. Common anionic surfactants are linear alkylbenzene sulfonate (LAS), alkyl sulfonate (AS), alcohol ether sulfate (AES) [15], etc.

Linear alkylbenzene sulfonate (LAS) is a widely used anionic surfactant, which accounts for 25%-30% of the synthetic surfactant. It is a mixture of more than 20 different components of homologues or isomers [16]. LAS has low toxicity to organisms and will not accumulate in organisms. It is easy to be biodegraded. The final degradation rate can reach about 80% [14]. In a sound activated sludge treatment system, the biodegradation rate of LAS can reach more than 90% and can even be completely removed [17]. The degradation degree of LAS is related to its molecular structure. The further the benzene ring is away from the central carbon atom, the more unstable the structure is, and the easier it is to be degraded [18]. The first step of degradation of LAS by microorganisms is the break of alkyl chain, forms carboxylic acid by  $\omega$ -oxidation of the terminal methyl group, and then forms acetyl-coenzyme A by  $\beta$ -oxidation to enter into tricarboxylic acid cycle; the last is the degradation of the benzene ring, which is oxidized by microorganisms to form  $\text{CO}_2$  and mineral salts, etc [19]. The degradation of benzene ring by microorganism is difficult, and it is a step of controlling speed in biodegradation. The strains capable of degrading LAS are *Pseudomonas nitroreducens*, *Pseudomonas aeruginosa*, *Pantoea agglomerans*, *Serratia odorifera* 2, etc [14, 20]. The degradation time, degradation conditions and degradation rate of different strains to LAS are different, so the best

degradation method is to select the most powerful strain or a combination of multiple strains for biodegradation.

Alkyl sulfonate (AS) can be easily biodegraded, the degradation speed is fast, and the rate of primary degradation can reach over 95% in a very short period of time [18]. Biodegradation of AS is accomplished by de-vulcanization of sulfate esterase and  $\beta$ -oxidation of aliphatic alcohols [21]. Sodium dodecyl sulfonate (SDS) is one of the most commonly used alkyl sulfonate anionic surfactants, which has low price and strong foaming ability and can be completely degraded into water and carbon dioxide by microorganisms. The strains capable of degrading SDS are *Pseudomonas putida* R1, *Acinetobacter calcoaceticus*, *Pantoea agglomerans* and so on [22, 23].

### 2.2. Cationic surfactants

Cationic surfactants can dissociate positively charged ions in solution, and are mainly used as fungicides, softeners and antistatic agents. Compared with the anionic surfactants, the dosage of the cationic surfactant is less. The hydrophobic group of the cationic surfactant is composed of an alkyl group, and the hydrophilic group is composed of a group containing nitrogen, phosphorus, sulfur and so on. At present, most of the cationic surfactants in industry are composed of nitrogenous compounds, which are classified into amine, quaternary ammonium, heterocyclic and rhodium salts.

Quaternary ammonium salts (QACs) are widely used in cationic surfactants because of their solubility in both acids and bases. QACs are organic compounds composed of four functional groups covalently attached to a positively charged central nitrogen atom. At least one of the four functional groups has a long hydrophobic alkyl chain, and the others are short chains such as methyl or benzyl [24]. Quaternary ammonium surfactants account for about 10% of the surfactant market and are widely used in pharmaceuticals, softeners, fungicides, preservatives, etc. [25]. QACs have strong germicidal effect and are easy to adsorb in the sediment, minerals or organic matter with positive charge in wastewater, which makes biodegradation more difficult [26]. The biodegradation of QACs mainly depends on the complexity of the molecular structure of QAC. The concentration of QAC and the resistance of microorganisms to QAC [24]. The strains capable of degrading QACs are *Pseudomonas sp.*, *Xanthomonas sp.*, *Thalassospira sp.*, *Aeromonas sp.* and so on [26]. There are three different mechanisms for biodegradation of QACs [25]: the first is that the hydroxylation of the alkyl chain takes place first and then goes through  $\omega$ -oxidation and  $\beta$ -oxidation to form acetyl CoA that enters into the tricarboxylic acid cycle; the second is that the alkyl chain is partially hydroxylated, followed by cleavage of the C-N bond under the action of the enzyme, and finally the degradation is completed by  $\beta$ -oxidation; the third mechanism suggests that in addition to long chain alkyl hydroxylation, hydroxylation and demethylation of methyl carbon also occur. Because of the differences in the structure of the strains and QACs components, the three mechanisms may exist alone or may coexist in multiple forms [27].

### 2.3. Nonionic surfactants

Nonionic surfactants cannot dissociate in solution to produce ions, and have high stability, which is the most commonly used type after anionic surfactants. The hydrophilic groups of nonionic surfactants are mainly composed of a plurality of oxygen-containing groups, such as hydroxyl and ether bonds. Due to the indissociability in the solution, the nonionic surfactant has high stability in solution and is not affected by acid and alkali, thus it has good advantages in washing, dispersion, foaming, solubilization and so on and is widely applied to the food, medicine, textile, paint and other industries. Common nonionic surfactants include alkylphenol polyoxyethylene ether (APEO), high carbon aliphatic alcohol polyoxyethylene ether (AEO), fatty acid polyoxyethylene ester (AE), etc.

Alkylphenol polyoxyethylene ether (APEO) mainly consists of octylphenol polyoxyethylene ether and nonylphenol polyoxyethylene ether, composed of a polyoxyethylene chain and an alkyl chain attached to a benzene ring, and it is widely used as an insecticide, emulsifier, and solvent enhancer [28]. Biodegradation of APEO mainly depends on the length and complexity of the alkyl chain as well as the number of elements in benzene ring and polyoxyethylene chain. The branched chain structure is

more difficult to degrade than the direct one, and the more units of polyoxyethylene chain it has, the more difficult it is to be degraded. APEO can be degraded by microorganisms to produce APEO with short polyoxyethylene chains, octylphenol, nonylphenol and other metabolites, among which octylphenol and nonylphenol are more toxic than APEO itself [29]. APEO metabolites are considered to be environmental endocrine disruptors that interfere with normal hormonal function and health status in animals and are associated with decreased sperm count in males, breast cancer, testicular cancer, and other diseases [18]. In order to reduce or even eliminate the effects of surfactants on the environment and microorganisms, the thorough biodegradation of APEO is essential. The strains capable of degrading APEO are *Pseudomonas sp.*, *Moraxella osloensis*, *Cupriavidus sp.*, *Brevibacterium sp.* TX4 and so on [28]. The biodegradation of APEO starts with the degradation of a single unit in the polyoxyethylene chain, the terminal hydroxyl group is oxidized to carboxylic acid, and a single unit of the polyoxyethylene chain is removed [30]. The degradation of alkylphenol is difficult for microorganisms, and the degradation mechanisms of different microorganisms are different. At present, there are two different degradation mechanisms: The first is that hydroxylation under the action of microbial enzymes can lead to the cleavage of alkyl chains and phenols, which in turn are degraded by microorganisms, respectively [31]; another mechanism is that alkylphenol forms alkyl catechol by the action of phenol hydroxylase, and then undergoes the cleavage of an aromatic ring by the action of dioxygenase, which is then biodegraded [32].

Aliphatic alcohol polyoxyethylene ether (AEO) is a mixture of many congeners, containing an alkyl chain of 12-18 carbon atoms connected to a polyoxyethylene chain of different unit count, which is widely used in decontamination, cleaning, care and other industries. Due to the poor biodegradability of APEO and the toxicity of its metabolites, APEO has been gradually banned in some areas, thus increasing the demand for AEO [33]. The strains capable of degrading AEO are *Pseudomonas aeruginosa*, *Pseudomonas stutzeri*, *Flavobacterium sp.* [34-36] and so on. The biodegradation of AEO occurs first with the breaking of the ether bond between the alkyl chain and the polyoxyethylene chain to form fatty acids and polyethylene glycols, and then the metabolites are finally biodegraded, respectively [37].

#### 2.4. Amphoteric surfactants

Amphoteric surfactants also have internal independent positive and negative charge centers; Amphoteric ionic surfactants (zwitterionics), on the other hand, refer to surfactants whose amphoteric properties are independent of pH over a wide pH range. Amphoteric surfactants include amphoteric surfactants (amphoterics) and amphoteric ionic surfactants (zwitterionics). Compared with the other three surfactants, amphoteric surfactants have a more mild effect on skin and eyes and are applied to daily necessities and cosmetics. However, due to high cost and complex synthesis, the production of amphoteric surfactants is not high. Amphoteric surfactants mainly include amino acid amphoteric surfactants, betaine type amphoteric surfactants and imidazoline surfactants.

The cationic part of betaine type amphoteric surfactant is composed of quaternary ammonium salt, which can be divided into carboxylate betaine, sulfobetaine and phosphate betaine according to different anions. The structure of the betaine type surfactants is based on the substitution of methyl or carboxyl groups of trimethylglycine with different substituents. Betaine type surfactants are relatively easy to biodegrade and their primary biodegradation rate can reach 100% [38]. Strains capable of degrading betaine surfactants are *Desulfobacterium*, *Eubacterium limosum*, *Sporomusa ovata* and so on [39-41].

#### 2.5. Biosurfactants

Biosurfactants are amphiphilic compounds produced in living surfaces, mostly on microbial cell surfaces or excreted extracellular hydrophobic and hydrophilic moieties that confer the ability to accumulate between fluid phases, thus reducing surface and interfacial tension at the surface and interface respectively [42]. They possess the characteristic property of reducing the surface and interfacial tension using the same mechanisms as chemicals surfactants [43]. Biosurfactants are mainly

classified according to their chemical structure and their microbial origin. The main classes of biosurfactants are glycolipids, phospholipids, polymeric biosurfactants and lipopeptides (surfactin).

### 3. Biodegradation mechanism of surfactants

The microorganisms take surfactants as carbon source to carry out degradation reaction under the catalysis of enzymes in the following ways:  $\omega$ -oxidation,  $\beta$ -oxidation,  $\alpha$ -oxidation, and benzene ring oxidation [44].

#### 3.1. $\omega$ -oxidation

Biodegradation of alkyl chains begins with  $\omega$ -oxidation of the terminal methyl group. As shown in Figure 1, the alkyl chain first generates a terminal alcohol under the action of alkane monooxygenase; the terminal aldehyde and the carboxylic acid are sequentially generated under the action of the two kinds of dehydrogenases.



Figure 1.  $\omega$ -Omega Oxidation Pathway.

#### 3.2. $\beta$ -oxidation

$\beta$ -oxidation continues to degrade the alkyl chain on the basis of the formation of carboxyl groups by  $\omega$ -oxidation of the alkyl chain. As shown in Figure 2, in  $\beta$ -oxidation, the carboxyl and coenzyme A are first esterified; alpha and beta carbon-carbon double bonds are formed under the action of dehydrogenase; beta-hydroxy group is generated under that action of hydrolytic enzyme; dehydrogenase is catalyzed and then beta-ketone is generated; finally, acetyl coenzyme A and fatty acid coenzyme A ester with less than two carbons are produced by interaction with coenzyme A. The above steps are repeated to complete the biodegradation of alkyl chains.

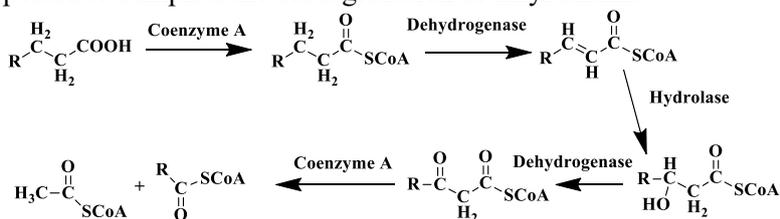


Figure 2.  $\beta$ -oxidation Pathway.

#### 3.3. Benzene ring oxidation

The oxidation link of benzene ring is the speed control step of surfactants with benzene ring. As shown in Figure 3, first, the benzene ring generates catechol under the action of oxygenase; then ortho-cleavage or meta-cleavage occurs under the action of oxygenase. Hexadiene diacid is generated by cleavage of the adjacent position, and the final degradation of acetic acid and succinic acid; 2-hydroxyhexadiene semialdehyde acid is generated by meta-cleavage, and finally the formic acid, acetaldehyde and pyruvic acid are formed [44].

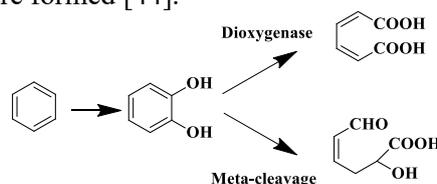


Figure 3. Oxidation Pathway of Benzene Ring.

#### 4. Factors affecting biodegradation of surfactants

As can be seen from the foregoing, the chemical structures of surfactants, such as the length and branching degree of alkyl chains, the number of units of polymers, benzene rings and their positions, have a great influence on their biodegradation. In addition, the kinds and concentrations of microorganisms, conditions of degradation reaction, types of surfactants in wastes and their availability all influence the progress of biodegradation [13].

##### 4.1. Microorganisms

As shown in table 1, for the same organic compound, there are many strains of different genera that can biodegrade it, but their degradability is not the same. It is very important for the biodegradation of specific compounds to screen out strains with strong adaptability and fast degradation. The degradation of organic matter by two or more strains in combination can increase the degradation rate and final degradation rate of organic matter, but the optimal degradation conditions are difficult to be controlled [45, 20, 22]. Khaled's study found that the degradation rate of LAS increased to 70% when LAS was degraded by a combination of two strains, namely, *Pantoea* and *Serratia odorifera*, far greater than the rate of degradation of LAS by a single bacterium (25%, 30%) [20]. The concentration of different microorganisms has a great influence on the degradation results. At low concentration, the microorganism has long adaptation time to substrate, slow growth and proliferation, and poor degradation ability. When the concentration is too high, the compounds are easily adsorbed on microorganisms, which affect the degradation results. Therefore, it is necessary to change the microbial concentration according to the degree of biodegradation of compounds. [20]

##### 4.2. Reaction conditions

**Table 1.** A table with biodegradation of different surfactants.

Surfactant	Strain	Degradation conditions	Determination method of degradation rate	References
Anionic type				
LAS	<i>Pseudomonas sp.</i>	pH 7.2 25°C	Methylene blue spectrophotometry HPLC	14
	<i>Pantoea agglomerans</i> <i>Serratia odorifera</i> 2.	pH 8.5 32°C	Methylene blue spectrophotometry HPLC	20
SDS	<i>Pseudomonas aeruginosa</i> S7	pH 7.2 30°C	Methylene blue spectrophotometry	23
Cationic type				
QACs	<i>Pseudomonas sp.</i>	pH 7.0 30°C	HPLC-UV HPLC-MS	26
	<i>Pseudomonas putida</i>	pH 7.0 37°C	GC-MS	47
Nonionic type				
APEO	<i>Brevibacterium sp. TX4</i>	pH 7.0 30°C	HPLC/MS	28
	<i>Pseudomonas sp.</i>	pH 7.0 28°C	HPLC	30
AEO	<i>Pseudomonas stutzeri</i>	pH 7.0 30°C	Chromatography	35
Bisexual				
Betaine type	<i>Eubacterium limosum</i>	pH 7.4 39°C	GC	39

### 4.3. Surfactants in wastes

Optimal reaction conditions are the prerequisite for efficient biodegradation. Temperature and pH are important but not the only conditions affecting microbial activity. Only at the most suitable temperatures and pH conditions do microorganisms grow and reproduce most readily and achieve maximum activity [46]. As shown in Table 1, that normal growth temperature of general microorganism is between 25-37°C, and the pH is about 7.0. The biodegradation of surfactants is divided into anaerobic and aerobic, and the need for oxygen varies according to the type of surfactant. For example, most cationic surfactants are degraded under aerobic conditions [26]; nonionic surfactants can be degraded under both aerobic and anaerobic conditions [30, 33]. The addition of additional carbon and nitrogen sources also changes the degree of biodegradation of the surfactant. For example, when sucrose was added as carbon source in the degradation of LAS, the rate of degradation of LAS was 9 mg/L/h, which was more than twice as high as that of glucose (4.5 mg/L/h); however, the addition of succinate as a carbon source inhibited the degradation of LAS (the degradation rate was 2.5 mg/L/h) [22].

The surfactant in waste or waste water is not only a single compound, but also a mixture of compounds. In addition to the matrix structure of surfactants, the compatibility, concentration and availability of compounds will all affect the degradation of surfactants. The degradation rate of the substrate compound by microorganisms varies depending on the concentration of the substrate compound, for example, when the concentration of LAS is 300mg/L, the degradation rate is 60%, but when the concentration increases to 700mg/L, the degradation rate falls to 10% [22]. When the concentration of the surfactant is too high, the microbial environmental adaptation takes a long time, and the activity of the microorganism is inhibited. The availability of microorganisms also greatly affects the progress of biodegradation [13]. Some compounds have poor solubility and are easily absorbed on solid particles; some compounds easily chelate with calcium and magnesium ions in water to form precipitates, which reduces their degradation rate [47]. Even if the same type of surfactant is present in the waste, the mixture of different components can change the degree of degradation. For example, Khan and other people used *Pseudomonas* to degrade benzyl dimethyl tetradecyl ammonium chloride (BDTA) and benzyl dimethyl dodecyl ammonium chloride (BDDA) in quaternary ammonium salt surface activity and found that BDTA inhibited BDDA's biodegradation; when only 10mg/L of BDTA was mixed in the system, the time required to completely degrade 100mg/L of BDDA increased from 100 hours to 150 hours [48].

## 5. Determination of biodegradability method

The degradation rate of the microbial degradation activity can be calculated by measuring the amount of surfactant before and after degradation over certain period. Commonly used determination methods are as follows:

### 5.1. Oxygen consumption method

The biodegradation of surfactants can be divided into aerobic and anaerobic degradation. In the process of aerobic degradation, surfactants need to be oxidized and degraded by microorganisms with the participation of oxygen. Therefore, the consumption of oxygen can be used as an indicator to evaluate the biodegradability. The commonly used methods to measure oxygen consumption are biological oxygen demand (BOD) method and chemical oxygen demand (COD) method [46]. BOD refers to the amount of dissolved oxygen required by aerobic microorganisms to degrade organic matter in water at a certain temperature and for a certain period of time. COD refers to the oxygen equivalent of compounds that can be oxidized by strong oxidizing agents, commonly used oxidizing agents are potassium dichromate, potassium permanganate, etc. Taking the BOD method as an example, the biodegradation rate of the surfactant is calculated as follows figure 4 [49].

$$\text{Biodegradation rate (\%)} = \frac{BOD - BOD_{\text{blank}}}{TOD} \times 100$$

$BOD_{\text{blank}}$ : oxygen variation of control group in the same condition without addition of microbial strain for a certain period of time

TOD: theoretical oxygen consumption required for complete degradation of surfactants

**Figure 4.** Computing method of Biodegradation rate of Oxygen consumption method.

### 5.2. Dissolved Organic Carbon (DOC) method

Dissolved organic carbon (DOC) method refers a process in which organic matter is degraded into carbon dioxide during the degradation of surfactant. Degradation capacity can be assessed by measuring the amount of carbon dioxide produced and converting it into organic carbon [50]. Commonly used methods for the determination of carbon dioxide include barium hydroxide method, TOC analyzer, etc. The biodegradation rate of surfactant in DOC method is calculated as follows figure 5 [51].

$$\text{Biodegradation rate (\%)} = \frac{C_T(\text{test}) - C_T(\text{control})}{C_0} \times 100$$

$C_T(\text{test})$ : change of organic carbon amount before and after degradation in a certain period of time

$C_T(\text{control})$ : change of organic carbon amount in control group under the same conditions without microbial strains for a certain period of time

$C_0$ : theoretical amount of organic carbon

**Figure 5.** Computing method of Biodegradation rate of Dissolved Organic Carbon (DOC) method.

### 5.3. Chemical quantitative method

Chemical quantitative method means that some surfactants can react with chemical reagents, so the amount of surfactant before and after the reaction can be measured to assess the degree of degradation, for example, the degradation of anionic surfactants can be measured by methylene blue method. Anionic surfactant can react with cationic dye methylene blue to produce blue products, which can be extracted with chloroform, and its absorbance at 655nm is proportional to its concentration [14]. The biodegradation rate of surfactants in methylene blue method is calculated as follows figure 6 [14]:

$$\text{Biodegradation rate (\%)} = 100 - \frac{A_{655} \text{ Experimental} - A_{655} \text{ Blank}}{A_{655} \text{ Control}} \times 100$$

$A_{655}$  test: within a certain period of time, absorbance of the chloroform layer of the degraded solution

$A_{655}$  Blank: under the same condition, the absorbance of the chloroform layer of the microbial solution is not added for a certain period of time

$A_{655}$  Control: the chloroform layer absorbance of the solution before degradation

**Figure 6.** Computing method of Biodegradation rate of Chemical quantitative method.

In addition to the above methods, the surface tension method is often used as an indicator to assess the degree of degradation of surface activity [45]. With the development of technology, more and more precision instruments can be used to analyze the content of compounds in samples directly and quantitatively, for examples, high performance liquid chromatography (HPLC), gas chromatography (GC) and gas chromatography–mass spectrometry (GC-MS) [20, 52, 53].

## 6. Conclusions, prospective and future directions

Surfactants are widely applied in industry, agriculture, food, medicine and other industries, which bring convenience to people, but also cause serious environmental pollution and even threaten human health. The degradation of surfactant in environment is an urgent problem to be solved in China and over the world. Microbial degradation of surfactants is an efficient, safe, environmentally friendly and widely applicable degradation method. Studying more effective biodegradation methods, improving biodegradability evaluation methods and developing green surfactants are important topics in biodegradation research. In order to understand the biodegradation mechanism of surfactants, the relationship between structure and degradability should be used to guide the synthesis of new degradable green surfactants and reduce environmental pollution from the source of usage.

## Acknowledgment

This work was supported by National Key Research and Development Program (No. 2016YYF0202300) and Presidential Fund of CNIS (562017Y-5286).

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