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Mechanisms and Environmental Risks of Surfactants in Environmental Pollution Control

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Abstract. With the rapid development of industrialization and urbanization, environmental pollution has become one of the most important issues worldwide. Because of the amphiphilic molecular structure and strong interfacial activity, surfactants exhibit great potential in environmental remediation through promoting dispersion, solubilization and degradation of pollutants.This review summarizes the main mechanisms of surfactants for pollution control, including reducing the consumption of chemical reagents, promoting elution and degradation of contaminants, and enhancing the efficiency of microbial remediation. In addition, this review analyze the environmental and ecological risks caused by surfactants, such as secondary pollution, bioaccumulation, and persistence in water bodies. The discussion highlights the importance of balancing remediation performance and ecological safety. This review focuses that the development of degradable, low toxicity and functional tunable surfactants is the trend of future green and sustainable remediation technology. This review provides a scientific reference for the rational design and application of surfactants in future environmental governance.

Keywords: Surfactant Environmental Protection, Environmental Pollution, Environmental Risks

1. Introduction

In these years, surfactants have been studied extensively for environmental remediation applications owing to their special interfacial activity, which showed the great potential in environmental water and soil contamination remediation.

Environmental pollutants are often having high reaction thresholds and poor dispersibility, which creates difficulties in their effective treatment. Surfactants are a group of substances which are able to decrease surface activation energy and therefore accelerate the natural processes of remediation processes or reduce the reaction barriers of certain contaminants. They promote dispersion of pollutants, maximizing the accessibility of pollutants to degradation processes, and can even be involved in chemical conversions to more easily degradable forms of a pollutant. The advantages of surfactants are in the ability to increase reaction to run faster and further.

Even at low concentrations, they can reduce the environmental impact, while complementary with other remediation processes, such as microbial degradation and electrochemical processes,

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hence promoting multifaceted decomposition processes. For example, surfactants can be used to improve spreading of droplets on hydrophobic plant surfaces during agricultural applications [1]. Additionally, they participate in the clumping of proteins on the interface and allow to predict the biosurfactant needs [2]. By decreasing the interfacial tension, surfactants facilitate dispersion of reactants and increases the specific surface area, therefore increases rates and efficiency of the reaction. This makes them extremely applicable in soil and water treatment systems, though, due to their widespread usage, they have also resulted in a significant distribution across the environment [3]. However, the use of surfactants is accompanied by some risks of environmental pollution, including promotion of harmful side reactions and secondary pollution. This review focuses on the summary of the mechanism of surfactant action in pollution control along with the discussion of corresponding environmental risks. Academically, this work contributes to optimization of environmental remediation technologies, whereas it serves as practical guidelines for pollution management.

2. Methodology

This article uses the literature review methodology. The main search was performed on the ACS database, focused on literature to be found simultaneously in the keywords 'surfactant' and 'environmental pollution'. The emphasis was there to be placed on high impact studies published in the last 5 years, while seminal studies with high citation counts published in older time periods also have been included.

2.1. Surfactant application in industrial processes reduces the required dosage of auxiliary chemicals

In both industrial and domestic contexts, surfactants participate in numerous chemical processes within production systems, thereby achieving the objective of reducing the dosage of other chemical agents. In reference [1], researchers utilized polydiallyldimethylammonium chloride-coated cellulose nanocrystals (PCNC) mixed with the anionic surfactant sodium dodecyl sulfate (SDS). This combination enabled the use of lower surfactant concentrations to enhance the dispersion of pesticides on hydrophobic plant surfaces, consequently reducing the required amounts of both pesticides and surfactants while mitigating their environmental impact. Table 1 compares the surface tension characteristics between the PCNC/SDS composite and pure SDS, demonstrating that the composite system can significantly reduce the required dosage. Furthermore, surfactants are widely incorporated into spray solutions to increase the solubility of active ingredients, improve the wettability of the plant epidermis, and enhance cuticular permeability, thereby boosting the efficacy of foliar-applied agrochemicals [4]. Table 1shows comparison of surface tension between surfactant and composite formulation

Table 1. Comparison of surface tension between surfactant and composite formulation

Samples	Ym(mN/m)	t*(ms)	N
0.1 wt% SDS	54.23	5.9	0.35
0.1 wt %SDS 0.5 wt%PCNC	45.31	1636.3	1

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2.2. Elution and degradation in soil remediation

In soil remediation, surfactants primarily enhance the elution and degradation of reactants. Taking the elution and recovery of petroleum resources as an example: In the remediation of petroleum-contaminated soil, as illustrated in the accompanying figure, a mixture of 95 g quartz sand, 5 g oil, and 200 g of DUSNa solution (20 mmol/L, pH 13) was added to a glass SESW bath. After two hours of stirring at room temperature, emulsions and cleaned sand were obtained through simple filtration. Phase separation was observed following CO_2 treatment, yielding distinct oil and aqueous phases. Subsequent NaOH treatment enabled further cleaning in the SESW bath. After this cleaning process, the residual oil in the sand (denoted as 5c) accounted for approximately 3.2% of the total oil, with a recovery rate of about 92.1%. Approximately 95.2% of the DUSNa remained in the aqueous phase. After two cycles of DUSNa reuse, the residual oil decreased to 2.8% of the total, resulting in an oil recovery rate between 93.4% and 94.1%. However, the amount of DUSNa in the aqueous phase decreased from 95.2% to 90.8% after two uses. Following filtration of the aqueous phase through a 0.22 μm membrane filter, the TOC and COD values of the filtrate were estimated at 402.2 mg/L and 634.7 mg/L, respectively, which were significantly lower than those of the SDS control group (3276.8 mg/L and 6778.4 mg/L, respectively). After further treatment of the resulting products with activated carbon and ion exchange resins, the TOC and COD levels were reduced to 19.1 mg/L and 35.6 mg/L. Thus, it can be concluded that the wastewater treatment process employing DUSNa in SESW is simple and efficient [5]. Therefore, surfactants can significantly improve the elution efficiency of petroleum-contaminated soil, and the DUSNa system demonstrates a lower pollution load compared to SDS, facilitating its recycling and reuse. Figure1 shows the elution flow chart.

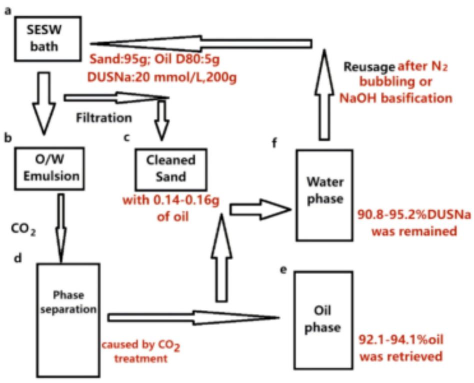

Figure 1. Elution flow chart

2.3. Application in Microbial Remediation

Application in the sphere of Microbial Remedial It was found that the addition of trace concentrations of the sodium dodecyl sulfate (SDS), even as low as 0.01 mM, caused a major increase in diffusiophoretic migration. This phenomenon was also shown in a consistent manner for all bacterial species tested. However, while surfactants have been shown to improve the motility of surface-attached bacteria by sliding mechanisms, or to mobilize bacteria entrained in sessile droplets by solutal Marangoni flows, here we show that of whatever type, surfactants can enhance freely suspended bacteria's diffusive migration by substantially boosting their motility with extremely low concentrations. The results have shown that, even at low concentrations, SDS enhances the diffusive migration of bacteria, implying that the effectiveness of microbial removal will be supported [6]. However, other studies have found that surfactants may lead to the increased toxicity of

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contaminants during anaerobic fermentation process and provide a dualistic nature to the synergistic interaction of surfactants and microorganisms [7].

2.4. Environmental contamination from Surfactants and Remediation Strategies

Contamination of Environment by Surfactants and Remediation Strategies During anaerobic fermentation of waste activated sludge (WAS), the functional microorganisms play an important role in volatile fatty acid (VFAs) biosynthesis. In addition, in this study the changes in the microbial community structure under different treatments were examined in order to further understand the relationship between the combination of surfactant and $Fe2O3$ nanoparticles (NPs) for VFA production. Co-contamination reduced the microbial richness and was shown in this study. It was well demonstrated that the surfactant produced a changed microbial distribution. In addition, the abundances of Firmicutes and Bacteroidota decreased in the systems with the coexistence of contaminants, and were negatively correlated to the concentration of $Fe2O3$ NPs. In this way, the presence of surfactants and $Fe2O3$ NPs had inhibited the number of acid-producing bacteria. In addition, the presence of surfactants and $Fe2O3$ NPs suppressed the energy metabolism of the anaerobic microorganisms. In conclusion, surfactants (especially LAS) and $Fe2O3$ NPs co-existed, and this resulted in the abundance of genes involved in fermentative substrate metabolism and VFA biosynthesis being decreased and consequently VFA production decreased [8]. It can be concluded therefore that co-existence of surfactant with nanoparticles modifies the microbial community structure, decreases the abundance of acid-producing bacteria and the VFA generation which implies potential environmental risks. In addition, surfactants have been demonstrated to be an efficient treatment option for contaminants like organophosphorus pesticides to increase the contaminant degradation via the surface tension effect. Considering the reaction mechanism, it can be deduced that the effect of surfactants can be expected in most reactions that request a reduction of surface tension [9].

2.5. Surfactants and water pollution

Under conditions of water pollution, surfactants are distributed in both surface water and groundwater. Their varieties and relative abundances reflect a certain degree of accumulation of commonly used surfactant agents in aquatic environments [10]. When treating wastewater derived from pollutant remediation, surfactant-based treatment schemes can be employed, which simultaneously minimize the generation of secondary wastewater and align with sustainable development pathways [11]. In the context of water pollution, while demonstrating efficacy in various applications, surfactants must also be recognized as a category of non-negligible pollutants. Consequently, their use warrants careful consideration to avoid the introduction of new contaminants, and attention must be paid to the treatment of the surfactants themselves.

3. Conclusion

This review has systematically analyzed the two sides of surfactants in environmental remediation which reveal their great potential and the associated risks. The main conclusions are as follows: First of all, surfactants demonstrably improve agricultural production processes and have the capacity of reducing the application rates of other pollutants. Second, they are effective in nauseation of the recovery and decomposition of contaminants in soils, being, as such, prone to elution. Third, through the combination with microbial remediation strategies there are very large synergies

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between the surfactants and the native microbial communities; however their interaction with native microbial populations requires pre-application evaluation under certain environmental conditions. Fourth, the potential of surfactants to inadvertently promote harmful side reactions emphasises the necessity of preliminary analysis to ameliorate the potential for such.

All together these results suggest that surfactants have a common merit within the area of environmental pollution control: they are highly effective in low concentration. However, the application strategies have to be adapted to specific contaminants and reaction systems. Consequently, previous analysis of application is necessary in order to avoid both the promotion of adverse reactions, and surfactant overdosing.

Future research should concentrate in the following directions: First of all, design and development of green and biodegradable surfactants to help to fight the risks of secondary pollution. Second, enhancing the knowledge of surfactant processes in complex environmental systems so as to prevent catalyzing a harmful reaction. Third, enhancing coupling of the simulated studies with real-world scenarios to promote the technical reality of surfactant-based technologies for practical engineering applications.

References

[1] Cao, G., Zhao, W., Han, L., Teng, Y., Xu, S., Nguyen, H., & Tam, K. C. (2024). Enhancing droplet spreading on a hydrophobic plant surface by surfactant/cellulose nanocrystal complexes. ACS Nano. https: //doi.org/10.1021/acsnano.4c13542

[2] Vargo, K. B., Stahl, P., Hwang, B., Hwang, E., Giordano, D., Randolph, P., Celentano, C., Hepler, R., & Amin, K. (2020). Surfactant impact on interfacial protein aggregation and utilization of surface tension to predict surfactant requirements for biological formulations. Molecular Pharmaceutics. https: //doi.org/10.1021/acs.molpharmaceut.0c00743

[3] Lindborg, A. R., Overdahl, K. E., Vogler, B., Lin, D., Sutton, R., & Ferguson, P. L. (2023). Assessment of long-chain polyethoxylate surfactants in wastewater effluent, stormwater runoff, and ambient water of San Francisco Bay, CA. ACS ES& T Water. https: //doi.org/10.1021/acsestwater.3c00024

[4] Li, Y., Chen, B., Chen, Z., & Zhu, L. (2009). Surfactant effects on the affinity of plant cuticles with organic pollutants. Journal of Agricultural and Food Chemistry. https: //doi.org/10.1021/jf803917w

[5] Xu, Y., Zhang, Y., Liu, X., Chen, H., & Fang, Y. (2018). Retrieving oil and recycling surfactant in surfactant-enhanced soil washing. ACS Sustainable Chemistry & Engineering. https: //doi.org/10.1021/acssuschemeng.7b04614

[6] Doan, V. S., Saingam, P., Yan, T., & Shin, S. (2021). A trace amount of surfactants enables diffusiophoretic swimming of bacteria. ACS Nano. https: //doi.org/10.1021/acsnano.0c07502

[7] Fang, S., Guo, W., Feng, Q., Cao, W., Dou, Y., Huang, W., Wang, F., Cheng, X., Cao, J., Wu, Y., & Luo, J. (2022). Surfactants aggravated the biotoxicity of Fe_2O_3 nanoparticles in the volatile fatty acids' biosynthesis during sludge anaerobic fermentation. ACS ES& T Water. https: //doi.org/10.1021/acsestwater.2c00459

[8] Yamamoto, Y., Tokonami, S., & Iida, T. (2018). Surfactant-controlled photothermal assembly of nanoparticles and microparticles for rapid concentration measurement of microbes. ACS Applied Bio Materials. https: //doi.org/10.1021/acsabm.8b00838

[9] Sharma, R., Gupta, B., Yadav, T., Sinha, S., Sahu, A. K., Karpichev, Y., Gathergood, N., Marek, J., Kuca, K., & Ghosh, K. K. (2017). Degradation of organophosphate pesticides using pyridinium-based functional surfactants. ACS Sustainable Chemistry & Engineering. https: //doi.org/10.1021/acssuschemeng.6b01878

[10] Burdette, T. C., Bramblett, R. L., Deegan, A. M., Coffey, N. R., Wozniak, A. S., & Frossard, A. A. (2022). Organic signatures of surfactants and organic molecules in surface microlayer and subsurface water of Delaware Bay. ACS Earth and Space Chemistry. https: //doi.org/10.1021/acsearthspacechem.2c00220

[11] Krell, C., Schreiber, R., Hueber, L., Sciascera, L., Zheng, X., Clarke, A., Haenggi, R., Parmentier, M., Baguia, H., Rodde, S., & Gallou, F. (2021). Strategies to tackle the wastewater from α-tocopherol-derived surfactant chemistry. Organic Process Research & Development. https: //doi.org/10.1021/acs.oprd.0c00547