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Surfactants in Water: Environmental Consequences

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SUMMARY

Surfactants are organic compounds with both solvent-loving and solvent-fearing groups, widely used in industries like agriculture, pharmaceuticals, cosmetics, and detergents. They exist in natural and synthetic forms, playing a key role in cell membranes and various applications. Surfactants enter aquatic environments through domestic wastewater, agricultural runoff, industrial spills, and atmospheric deposition, potentially harming ecosystems by disrupting cell membranes, causing foaming, and contributing to eutrophication. While some are biodegradable, others persist, requiring improved wastewater treatment, stricter regulations, and public awareness to mitigate risks. Sustainable alternatives and responsible disposal practices are essential for reducing environmental impact.

INTRODUCTION

Surfactants (or 'surface active agents') are organic compounds with at least one lyophilic ('solvent-loving') group and one lyophobic ('solvent-fearing') group in the molecule. Surfactants are a group of chemicals that touch our everyday lives in countless ways. They are present in our food, our drinks, the products that we use to clean ourselves, cars that we drive and clothes that we wear. The words surface active agents are combined to form surfactant. Surfactant is characterised by its tendency to adsorb at surfaces and interfaces. It is an organic compound and widely used in agriculture, pharmaceutical, biotechnology, nanotechnology, cosmetic, detergent, printing, recording, microelectronics, petroleum, mining and other industries. It exists in both natural and synthetic forms. Surfactants such as phospholipids are the main components of the cell membranes and sustain life by organising the order of chemical reactions. For a compound to be a surfactant, it should possess three characteristics: the molecular structure should be composed of polar and non-polar groups, it should exhibit surface activity and it should form self-assembled aggregates (micelles, vesicles, liquid crystalline, etc.) in liquids.

Classification of Surfactants and their Applications

There are many kinds of surfactants, and they are classified by use, properties and chemical structure. The surfactant classification depends on water dissociation and the structure of hydrophilic group. According to the water-soluble, surfactants can be classified into ionic surfactants and non-ionic surfactants. Ionic surfactants can be divided into anionic surfactants, cationic surfactants and amphoteric surfactant.

Anionic surfactants

The anionic surfactants are dissolved in water with generating the negatively charged surface active group, whose aqueous solution is neutral or alkaline. Hydrophilic groups according to the type of anionic surfactants can be divided into five peptide condensates: carboxylic acid salt type, sulfate salt type, sulfonate, phosphate ester and fatty acid salt type. Anionic surfactants are the earliest development, the biggest production and the largest species in various types of surfactants. They can be widely used as detergents, foaming agents, emulsifiers, antistatic agents, dispersants and stabilizers in the family and chemical aspects of life.

Cationic surfactants

Cationic surfactants are dissolved in water with generating the surface activity positive ions. They have good surface activity in an acidic medium and are likely to precipitate and lose activity in alkaline medium. Cationic surfactants are classified into open-chain cationic surfactants, heterocyclic group cationic surfactants and bonded intermediate connection cationic surfactants according to the chain structure. Cationic surfactants are widely used for sterilization, rust, corrosion, breaking, corrosion and mineral flotation.

Amphoteric surfactants

Amphoteric surfactants which take with both positive and negative ions can be divided into imidazoline, betaine, lecithin, and amino acid-type type according to the anion type. The toxicity of amphoteric surfactants is very low. It is gentle to the skin, and has good biodegradability. Amphoteric surfactants have wide application in the personal protective equipment such as shampoo, shower gel, cosmetics, etc. and also can be used in industrial softeners and antistatic agents.

Non-ionic surfactants

Non-ionic surfactants did not ionize any form of ions in an aqueous solution, and a number of oxygen-containing groups form hydrophilic, achieving dissolution by hydrogen bonding with water. Most of non-ionic surfactants are in liquid and slurry form, their solubility in water decrease with the increasing temperature. Non-ionic surfactants have different physicochemical properties from ionic surfactants due to their structural features. Hydrophilic groups are divided into four categories such as polyethylene glycol type, polyhydric alcohols, polyether type and glycosidic type. Non-ionic surfactants are widely used in the textile, paper, food, plastic, glass, fiber, medicines, pesticides, dyes and other industries. They are a lot better performance than ionic surfactants, the production is second to the anionic surfactants.

Macromolecule surfactants

Macromolecule surfactants generally refer to polymeric surfactants whose relative molecular mass are greater than 10000, having a surface-active substance. According to the natural source, they can be divided into natural type, modified natural material and composing categories. Polymer surfactants can be used as thickener, gelling agent, fluidity-improving agent, emulsifier, dispersing agent and antistatic agent. It has become an important member of the surfactants family.

Bio-surfactants

Bio-surfactants refer to culturing the microorganism under certain conditions, dissolving out surface active metabolites in its metabolism. Depending on the chemical structure, biological surfactants can be divided into single sugar esters, polysaccharides esters, proteins and phospholipid esters. Bio-surfactants are widely applied in the petrochemical industry, and are extensively used for emulsification, emulsion breaking, wetting, foaming and anti-static. They also have important applications in the textile, cosmetics, pharmaceutical, food and other fields.

Source of Surfactants in Water

Surfactants enter aquatic environments through various **natural** and **anthropogenic (human-made)** sources. These include wastewater discharge, industrial effluents, agricultural runoff, and stormwater.

1. Domestic Wastewater (Households & Municipal Waste)

Household activities contribute significantly to surfactant pollution, primarily from:

Detergents and Laundry Wastewater

Surfactants in **laundry detergents** (e.g., linear alkylbenzene sulfonates (LAS), alcohol ethoxylates) reach water bodies through wastewater discharge. Incomplete treatment in sewage treatment plants (STPs) can lead to surfactant accumulation in rivers and lakes.

Personal Care Products (PCPs)

Shampoos, soaps, body washes, and toothpastes contain surfactants such as **sodium lauryl sulfate (SLS)** and **cocamidopropyl betaine**. These chemicals enter wastewater systems daily and may not fully degrade before reaching natural waters.

Household Cleaning Products

Dishwashing liquids, floor cleaners, and all-purpose cleaners contain surfactants like **nonionic and anionic surfactants** (e.g., alcohol ethoxylates, LAS).

These products are often washed down drains, adding to the surfactant load in wastewater.

Pharmaceuticals and Cosmetics

Some pharmaceutical formulations (e.g., **creams, ointments, emulsions**) and cosmetics (e.g., **makeup removers, lotions**) contain surfactants.

Their residues enter water bodies through washing, bathing, and improper disposal.

2. Agricultural Runoff:

Pesticide and Herbicide Formulations: Surfactants are often added to pesticide and herbicide formulations to improve their wetting, spreading, and penetration properties. These surfactants help the active ingredients adhere to plant surfaces and increase their effectiveness.

Impact: Runoff from agricultural fields can carry these surfactants into nearby water bodies.

Examples: Nonylphenol ethoxylates (NPEs): Though their use is restricted in many areas, they are still present in older formulations or used in some regions. Organosilicone surfactants: Used for super-spreading properties.

Fertilizers: Some liquid fertilizers may contain surfactants to improve their distribution and uptake by plants.

Impact: Runoff following fertilizer application can contribute to surfactant contamination.

3. Accidental Spills:

Transportation Accidents: Accidents involving trucks, trains, or ships carrying surfactants can lead to direct releases into water bodies.
Storage Tank Leaks: Leaks from storage tanks at industrial facilities or distribution centers can contaminate soil and groundwater, which can then migrate to surface water.
Industrial Accidents: Accidents at industrial facilities that use or manufacture surfactants can result in uncontrolled releases into the environment.

4. Atmospheric Deposition:
This is often a less significant but still relevant pathway.
Atmospheric Transport: Some surfactants can be volatilized or become attached to particulate matter and be transported through the atmosphere.
Wet and Dry Deposition: These surfactants can then be deposited into aquatic environments via rainfall (wet deposition) or dry deposition (settling of particles). *Examples:* Some studies have found trace amounts of surfactants in remote areas far from direct sources, suggesting atmospheric transport.

5. Other Minor Sources:
Firefighting Foams: Some firefighting foams contain surfactants that can enter water bodies during training exercises or actual fire incidents.
Recreational Activities: Soaps and shampoos used during swimming or boating can contribute small amounts of surfactants to water.
Direct Application: In some cases, surfactants may be directly applied to water bodies for specific purposes, such as oil spill cleanup or algae control.

Aquatic Toxicity

According to Ying (2006), different types of surfactants have been detected in sewage effluents with concentrations up to 1090 $\mu g\ L^{-1}$ for anionic surfactants (e.g., LAS), up to 332 $\mu g\ L^{-1}$ for non-ionic surfactants (e.g., AFEOs), and up to 62 $\mu g\ L^{-1}$ for cationic surfactants (e.g., DTDMAC). Although efficient treatment in wastewater plants will result in discharge of very low levels of surfactants in the environment, the massive release of these compounds exposes a wide variety of aquatic ecosystems to potential risks.

1. Toxicity to Aquatic Organisms:
Mechanisms of Toxicity:
Cell Membrane Disruption: Surfactants can disrupt the structure and function of cell membranes, leading to cell damage or death. The hydrophobic portion of the surfactant can interact with the lipid bilayer of the cell membrane, disrupting its integrity.
Gill Damage: In fish and other aquatic organisms that breathe through gills, surfactants can damage the delicate gill tissues, impairing their ability to extract oxygen from the water. This can lead to suffocation.
Interference with Osmoregulation: Surfactants can disrupt the osmoregulatory processes in aquatic organisms, affecting their ability to maintain the proper balance of water and salts in their bodies. This can lead to dehydration or swelling and, ultimately, death.
Enzyme Inhibition: Some surfactants can inhibit the activity of essential enzymes in aquatic organisms, disrupting metabolic processes.

2. Eutrophication:
Some surfactants can contribute to nutrient enrichment.
Phosphorus Content: Some surfactants, particularly older formulations, contain phosphorus. When these surfactants enter water bodies, the phosphorus can act as a nutrient, stimulating the growth of algae and aquatic plants.
Algal Blooms: Excessive nutrient enrichment can lead to algal blooms, which can have several negative consequences:
Oxygen Depletion: As algae die and decompose, the decomposition process consumes oxygen, leading to hypoxia (low oxygen levels) or anoxia (no oxygen) in the water. This can kill fish and other aquatic organisms.
Toxin Production: Some types of algae produce toxins that can be harmful to aquatic organisms and humans.
Reduced Light Penetration: Algal blooms can reduce the amount of light that penetrates the water, inhibiting the growth of submerged aquatic plants.

3. Foaming:
This is a more visible and aesthetic impact.
Surface Tension Reduction: Surfactants lower the surface tension of water, making it easier to form stable bubbles.
Foam Formation: When water containing surfactants is agitated, such as in rivers with rapids or near wastewater treatment plant outfalls, foam can form.

Negative Consequences:

Aesthetic Nuisance: Foam can be unsightly and detract from the recreational value of water bodies.

Reduced Oxygen Transfer: Excessive foam can interfere with the transfer of oxygen from the air to the water, potentially exacerbating oxygen depletion problems.

Interference with Navigation: In some cases, foam can interfere with boat navigation.

4. Indirect Effects:

Surfactants can also have indirect effects on aquatic ecosystems.

Increased Solubility of Other Pollutants: Surfactants can increase the solubility of other pollutants, such as hydrophobic organic compounds (e.g., pesticides, PCBs), making them more mobile and bioavailable.

Alteration of Microbial Communities: Surfactants can alter the composition and activity of microbial communities in aquatic environments, which can have cascading effects on nutrient cycling and other ecosystem processes.

Synergistic Effects: The effects of surfactants can be amplified when they are present in combination with other pollutants.

CONCLUSION

In conclusion, surfactants, while essential components of many everyday products and industrial processes, pose a significant and multifaceted threat to aquatic environments. Their amphiphilic nature leads to a wide array of impacts, ranging from direct toxicity to aquatic organisms through cell membrane disruption and gill damage, to indirect effects like eutrophication, foaming, and endocrine disruption. The ability of some surfactants to enhance the solubility and bioavailability of other pollutants further exacerbates their potential harm. While some surfactants are readily biodegradable, others persist in the environment, accumulating in sediments and potentially entering the food chain. Addressing the challenges posed by surfactants requires a comprehensive and integrated approach. This includes promoting the development and use of readily biodegradable and less toxic surfactant alternatives, upgrading wastewater treatment infrastructure to enhance surfactant removal, implementing stricter regulations on surfactant discharge, and fostering greater public awareness regarding the responsible use and disposal of surfactant-containing products.

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