

MEMBRANE TECHNOLOGY

Engineering, design, and optimization of membrane processes for industry and research.

Antifoaming Agents in Membrane Technology: Impact on Ultrafiltration Performance and Fouling

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Abstract

Antifoaming agents are widely used in industrial fermentation and membrane-based separation processes to control foam and maintain operational stability. However, their presence in ultrafiltration systems can induce membrane fouling, leading to pore blockage, adsorption, and reduced permeate flux. This study systematically investigates the interactions between antifoaming agents, defoamers, and polymeric ultrafiltration membranes, with particular emphasis on fouling mechanisms and performance decline.

Avoiding foam formation is the most effective strategy to minimize reliance on chemical antifoaming agents. Foam originates from air entrainment and is stabilized by surface-active compounds; thus, reducing air incorporation directly limits foam generation and associated process challenges. In contrast, conventional antifoaming formulations—typically composed of hydrophobic compounds such as silicone oils, polyethers, and fatty acid esters—persist in the system and promote fouling through surface deposition, pore constriction, and gel layer formation.

Fouling behavior is further governed by process conditions, including temperature, pH, hydrodynamics, and formulation-specific properties such as surfactant cloud points. These factors influence both foam stability and membrane–foulant interactions.

This white paper underscores the importance of integrating foam prevention strategies with optimized antifoaming agent selection and process conditions. Such an approach reduces membrane fouling, enhances ultrafiltration performance, and supports more sustainable and efficient bioprocessing.

Keywords: antifoaming agents, defoamers, ultrafiltration, membrane fouling, fermentation, permeate flux, surfactants, process optimization

1 Foam Formation in Biotechnological and Membrane Filtration Systems

1.1 Mechanisms of Foam Formation in Biotechnological Systems

Foam formation is a common phenomenon in biotechnological systems, particularly in fermentation and downstream processing operations. It arises from the dispersion of gas within a liquid phase, resulting in the formation of gas bubbles separated by thin liquid films. In aerobic bioprocesses, gas is intentionally introduced to supply oxygen, which inherently promotes foam generation. The presence of surface-active compounds stabilizes these gas–liquid interfaces and prevents rapid bubble coalescence.

Surface-active agents in biotechnological systems originate from multiple sources, including proteins, peptides, lipids, and extracellular polymeric substances released by microorganisms. These compounds adsorb at the gas–liquid interface and reduce surface tension, facilitating bubble formation and stabilization. Proteins, in particular, can form viscoelastic interfacial films that significantly enhance foam stability. As a result, foam persistence increases with biomass concentration and metabolic activity.

Hydrodynamic conditions play a critical role in foam generation. Agitation and aeration introduce shear forces that promote bubble breakup and increase interfacial area. High gas flow rates and turbulent flow regimes further enhance bubble dispersion and foam formation.

Foam formation is strongly influenced by system geometry and operating conditions. In bioreactors, sparger design and impeller configuration determine bubble size distribution and gas holdup. Foam

stability is governed by the balance between bubble formation and decay mechanisms, including liquid film drainage, bubble coalescence, and gas diffusion. In biotechnological systems, continuous gas input often exceeds foam decay rates, leading to persistent foam layers, particularly in long-duration processes.

Temperature and physicochemical conditions also affect foam behavior. Changes in temperature alter surface tension, viscosity, and surfactant solubility. For example, nonionic surfactants exhibit cloud point behavior, which modifies their interfacial activity and foam stability. Similarly, pH and ionic strength influence protein conformation and adsorption characteristics.

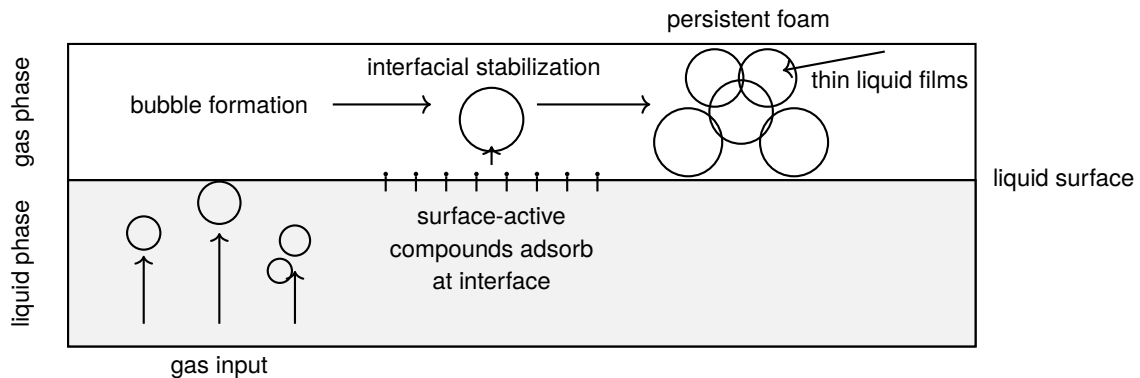


Figure 1. Principal mechanism of foam formation in biotechnological systems. Gas dispersion generates bubbles in the liquid phase; surface-active compounds adsorb at the gas–liquid interface and stabilize the bubbles; accumulation of stabilized bubbles at the liquid surface leads to persistent foam.

2 Foam Behavior and Impact in Membrane Filtration Systems

2.1 Foam Formation and Hydrodynamic Effects

In membrane filtration systems, additional mechanisms contribute to foam formation and propagation. Pumps, valves, and fittings can introduce air through leaks or vortex formation, leading to unintended air entrainment. This entrained air is transported into membrane modules, where it accumulates and contributes to foam development.

Hydrodynamic conditions specific to membrane processes, such as crossflow velocity and recirculation, further enhance shear forces and promote bubble dispersion. Foam can form both upstream of the membrane and within the membrane module itself. The presence of gas bubbles disrupts flow uniformity and alters local hydrodynamics.

2.2 Impact on Membrane Performance and Fouling Mechanisms

At the membrane surface, bubbles may adhere and block active filtration areas, reducing the effective membrane area available for filtration. This directly leads to a decline in permeate flux. In addition, foam promotes fouling by facilitating the deposition of surface-active materials onto the membrane surface.

The thin liquid films surrounding bubbles are enriched with proteins and surfactants, which readily adsorb onto membrane pores. Upon bubble rupture, these materials are deposited directly onto the membrane, accelerating fouling layer formation. This contributes to both reversible and irreversible fouling mechanisms.

Foam also intensifies concentration polarization effects. Disrupted flow patterns caused by bubbles enhance the accumulation of solutes near the membrane surface. This increases local viscosity and mass transfer resistance, further impairing filtration performance.

Overall, foam formation in membrane filtration systems results from the combined effects of air entrainment, surface-active compounds, hydrodynamics, and system design. Its presence not only compromises process stability but also significantly impacts membrane performance through fouling and flux decline. Understanding these interactions is essential for developing effective foam mitigation and membrane operation strategies.

3 Antifoaming Agents

Antifoaming agents are chemical additives specifically used to suppress foam formation. They are used particularly in fermenters and bioreactors.

Foam consists of gas bubbles (e.g., air) surrounded by thin liquid films. In biotechnology, it often forms due to gaseous metabolic products in combination with surface-active substances.

Uncontrolled foam formation can significantly disrupt operation. Antifoaming agents therefore contribute to process stability. Their effect is based on the destabilization of gas–liquid interfaces. In this process, foam lamellae are weakened or destroyed. In industrial fermentation, antifoaming agents are widely used. However, they may negatively affect downstream separation processes such as ultrafiltration.

3.1 Defoamers

The difference between antifoaming agents and defoamers lies less in their chemical class than in the timing, mechanism of action, and application. Although the terms are often used synonymously in practice, there is a clear technical distinction.

Antifoaming agents are applied preventively to inhibit or limit foam formation from the outset. Defoamers, in contrast, are applied correctively and are used for the rapid destruction of existing foam. Chemically, both substances may be identical. The distinction is based on timing and mode of application.

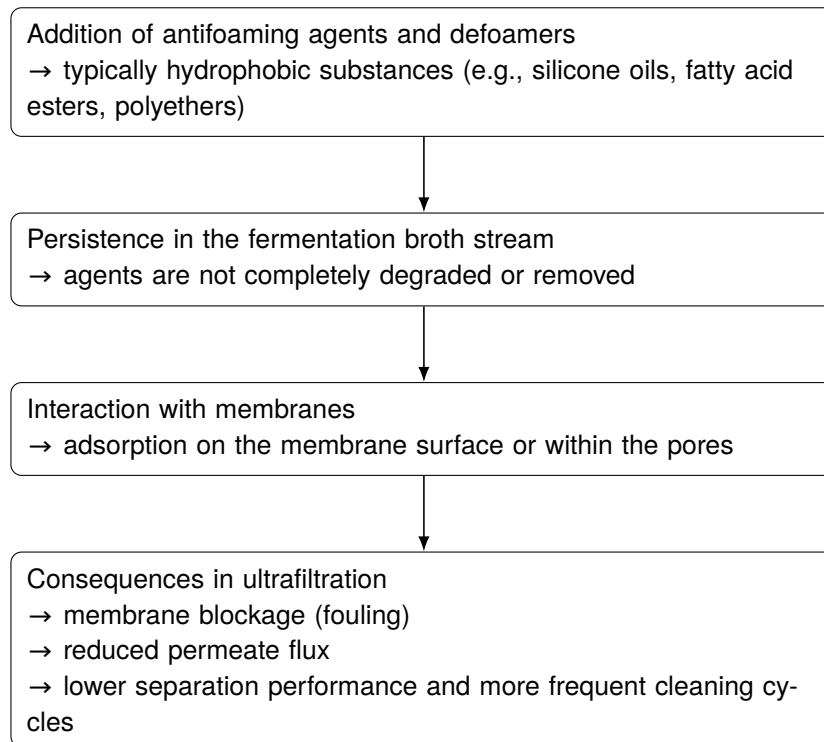


Figure 2. Cause–effect chain of antifoaming agents and defoamers in fermentation

4 Ultrafiltration

4.1 Interaction of Antifoaming Agents with Polymeric UF Membranes

The use of antifoaming agents in ultrafiltration systems introduces complex physicochemical interactions that can adversely affect membrane performance. In many cases, components of antifoaming formulations deposit on the membrane surface and penetrate into the porous matrix of polymeric ultrafiltration (UF) membranes. These deposits typically consist of hydrophobic compounds such as silicone oils, polyethers, and fatty acid derivatives, which exhibit strong affinity for polymeric materials. Such accumulation leads to partial or complete pore constriction, effectively reducing the membrane's nominal pore size. As a consequence, hydraulic permeability decreases, resulting in a measurable decline in permeate flux. In addition, the formation of hydrophobic fouling layers alters surface properties, reducing wettability and further impairing filtration efficiency.

Membrane cleanability is often significantly compromised. Adsorbed antifoaming components can resist conventional cleaning protocols due to their low solubility and strong adhesion to membrane surfaces. This contributes to irreversible fouling and long-term performance degradation. The phenomenon is consistent with established fouling models, including pore blocking and cake layer formation mechanisms.

The extent of these effects depends strongly on both membrane material and antifoaming agent composition. Polymeric membranes such as polyethersulfone (PES) or polyvinylidene fluoride (PVDF) exhibit different affinities toward hydrophobic foulants. Process parameters, including temperature, pH, and crossflow hydrodynamics, further influence adsorption kinetics and fouling layer structure. Elevated temperatures, for example, may enhance diffusion and adsorption rates, while pH affects the ionization state of surface-active compounds.

Therefore, the selection of antifoaming agents must be carefully aligned with membrane material and process conditions. Empirical validation through pilot-scale trials under realistic operating conditions is essential to assess fouling behavior and long-term system stability.

4.2 Effects of Defoamers on Membrane Fouling and Process Performance

The use of defoamers in ultrafiltration systems results in similar, yet distinct, interaction mechanisms compared to conventional antifoaming agents. Defoamers are typically designed to destabilize foam by promoting bubble coalescence; however, their chemical constituents can also interact with membrane surfaces.

In many cases, defoamer components adsorb onto the membrane surface and infiltrate the pore structure. This leads to pore narrowing or blockage, reducing effective membrane permeability and decreasing permeate flux. The presence of such materials also modifies surface energy characteristics, which can enhance the adsorption of additional foulants present in the feed stream.

Furthermore, defoamers often contain emulsifiers and surfactants that contribute to the formation of gel-like fouling layers. These layers increase hydraulic resistance and exacerbate concentration polarization effects. As a result, both reversible and irreversible fouling mechanisms are intensified.

The magnitude of these effects is governed by the interplay between membrane properties and defoamer chemistry. Parameters such as molecular weight distribution, hydrophobicity, and emulsion stability influence the extent of membrane interaction. Process conditions, including temperature, pH, and hydrodynamic regime, further modulate these interactions. For instance, temperature-dependent phenomena such as surfactant cloud points can alter solubility and phase behavior, thereby affecting fouling dynamics.

Consequently, careful selection and optimization of defoamer formulations are critical when operating polymeric UF systems. Compatibility with membrane materials and operating conditions must be systematically evaluated. Validation through pilot trials or application-specific testing is strongly recommended to minimize fouling, maintain membrane performance, and ensure robust downstream processing.

5 Fermentation

In fermentation, various types of antifoaming agents and defoamers are used. An important group includes silicone-based compounds, typically present as aqueous emulsions. In addition, silicone-containing systems in polyglycols as well as pure polyglycols without silicone are used. Since silicones are not water-soluble, emulsifiers are required to stabilize the distribution of the hydrophobic phase in the fermentation medium.

Several studies show that these additives in particular can negatively affect downstream membrane processes. Emulsifiers, surfactants, and thickeners are considered major contributors to membrane fouling in polymeric ultrafiltration membranes. Commonly used nonionic surfactants include glycerol monostearates, polyoxyethylene sorbitan stearates, and polyoxyethylene monostearates.

Many of these surfactants exhibit so-called cloud points, which describe temperature-dependent phase separation. Above the cloud point, surfactant molecules lose their hydration shell, causing micelles to grow significantly and resulting in macroscopic turbidity. In this state, surfactants can act as defoamers, whereas below the cloud point they may partially promote foam formation. Since fermentation processes are often operated at temperatures around 40 °C, these conditions are above the cloud points of many nonionic surfactants.

Cooling the process stream can improve downstream ultrafiltration but is often associated with significant energy demand in practice. Therefore, switching the antifoaming agent is often the more

economical solution.

In addition, many antifoam emulsions contain water-soluble thickeners. Typical examples include cellulose ethers and xanthan gum, which significantly increase the viscosity of aqueous solutions due to their long polymer chain structures. At elevated temperatures, these substances can form a gel point, resulting in a highly crosslinked polymer gel. It is assumed that a similar effect occurs on the membrane surface, where a stable gel layer may form. This layer represents an additional flow resistance and contributes significantly to the reduction of permeate flux.

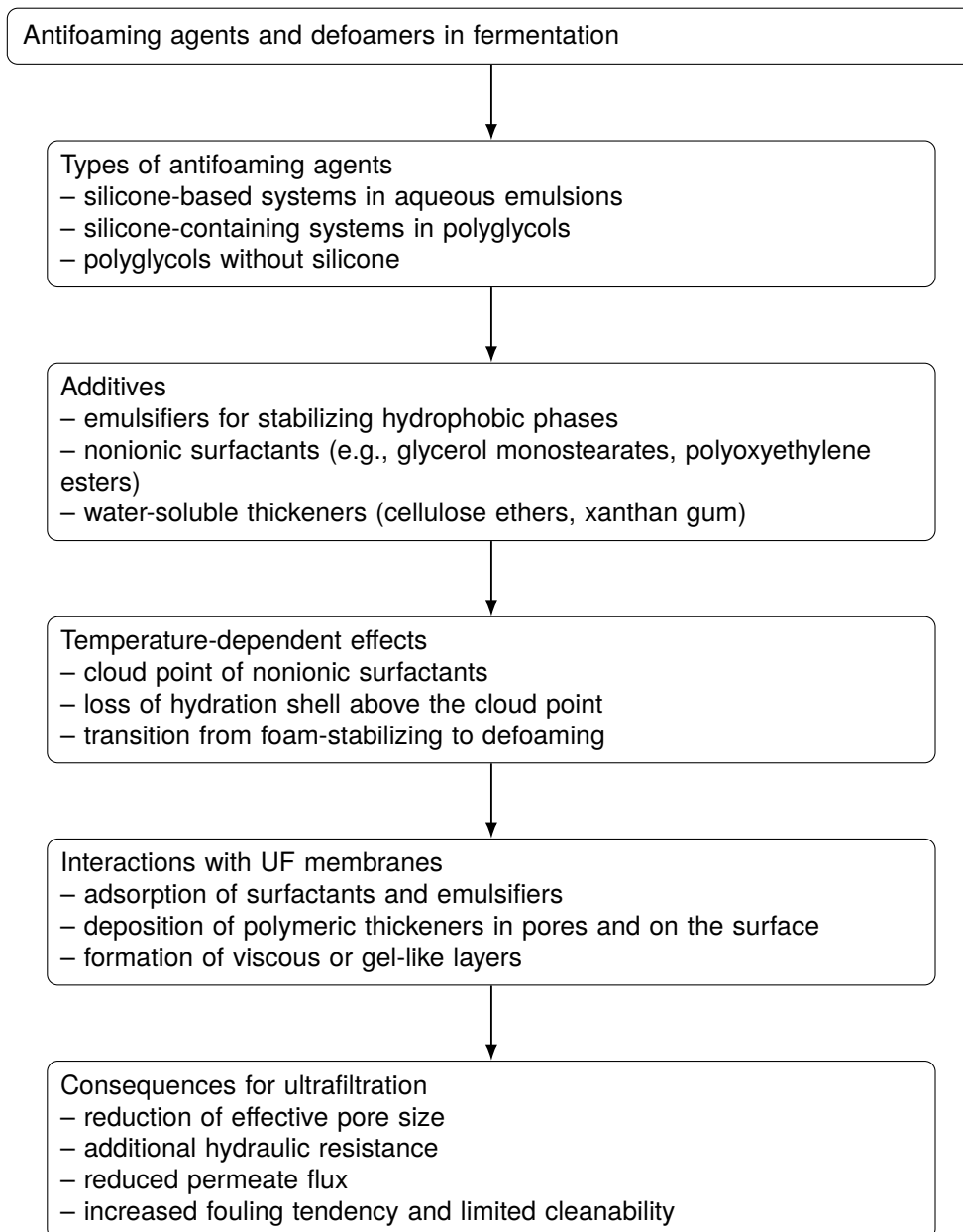


Figure 3. Schematic overview of the mechanisms of action of antifoaming agents and defoamers and their influence on polymeric ultrafiltration membranes in fermentation processes