

Foaming and defoaming—concepts and their significance in food and allied industries: a review

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Abstract

Foaming is an essential unit operation in several food processing industries. Although foaming is advantageous for a few industries, it causes huge losses in others. Foam generation as well as its stabilization is a complex phenomenon, and its efficient control is a mandatory operation in the food industry. Surface tension, viscosity, and ionic strength are the factors that influence foaming behavior. Film elasticity and the production of gelatinous surface layers are linked to the stability of persistent foams. Several chemicals, natural oils, esters, and fatty acids are found to be the components to reduce foaming during food processing. In the present review, the science behind foaming has been discussed in detail along with its stabilization, destabilization as well as different methods to control the foaming during processing. Here, the merits and demerits of foaming are also elaborated on with suitable examples. The current review also provides new insights into the application of foaming and defoaming substances in vegan industries and its effect on the stabilization and destabilization of foam at the air–water interface.

Keywords Aerated foods · Gas–liquid interface · Foaming · Food industry · Anti-foaming

1 Introduction

Scientific societies and researchers have shifted their focus to alternative, more sustainable food and agricultural systems in response to the growing trends in the current food system toward global integration, economic consolidation, and environmental devastation [1]. Recently, consumers are more concerned about human and environmental health and are interested in products that consist of natural and sustainable food ingredients [2]. The worldwide market is also moving towards a more sustainable mode of lifestyle, substituting synthetic components with natural ones; for instance, plant-based ingredients are replacing animal-based ingredients in various food products.

Foam is an essential component of different food commodities such as beverages like coffee, cappuccino, fruit juices, milkshakes, carbonated drinks, ice creams, whipped creams, wine, etc. Foam is a dispersion consisting of gas bubbles separated by thin liquid layers; it is also termed liquid–gas dispersion, where liquid serves as disperse phase and gas acts as the dispersion medium. Reportedly, not every dispersion is thermodynamically stable owing to its excess interfacial free energy. Due to the substantial difference in densities between the gas bubbles and the medium, the system rapidly

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divides into two layers by the upward flow of the gas bubbles to the top where they possibly will deform to create a polyhedral shape. Dilute surfactant solutions create a resorting force that works to restore the equilibrium as the water/air interface increases and disturbs the surface equilibrium [3]. Emulsifiers (phospholipids, plant proteins, sterols, saponins, Rhamnolipids, etc.), thickeners (polysaccharides, beet pectin, citrus pectin, gum arabica, etc.) [4], a variety of gums like guar gum, Gellan gum, and natural plant derived polysaccharides have been used for centuries for numerous applications, and they are considered invaluable ingredients in food, pharmaceutical as well as in cosmetic industries for providing excellent quality products with foaming ability, consistency, shelf stability, and consumer appeal [5–7]. Modern lifestyles and consumers' demands are expected to increase the requirements for these emulsifiers, hence, several research works are being carried out for the development of plant-based novel foam-forming and foam-stabilizing agents [8].

In a recent survey-based review, the authors discussed the current methods to control the foam in food and chemical industries, which was collected directly from operators and manufacturers through a survey [9]. Other published reviews regarding the influence of foaming in the food industry explain the defoaming mechanism, the action of defoaming, methods of defoaming, and its types such as slow and fast. In the current review, we have focused on both the foaming as well as defoaming mechanisms, the role of different surfactants in foaming, their mechanism of action, and applications in food and allied industries. The present review discusses in detail the mechanism of foam formation, foam stabilization, destabilization, and the importance of foaming with suitable examples. Different methods to control the foaming during processing have also been elaborated. The current review also explains the physicochemical and characteristic behavior of foaming and antifoaming agents, and provides new insights into the application of foaming and defoaming agents in vegan industries.

2 Science behind foaming

The fundamental principles of foaming mainly include the intramolecular interaction between components based on attraction and repulsion forces. It may occur covalently and non-covalently [10]. Bubbles form in the liquid phase as a result of topological fluctuations at the air–water interface. This process involves the production of small bubbles during the breakdown of a large bubble, as well as the separation of bubbles from the free surface or the purging nozzle. In a different instance, researchers pointed out that the formation of bubbles is not the result of a topological shift but rather of a phase transition or chemical reaction [11]. There are several ways of foaming, which are categorized as physical, chemical, and biological, elaborated in detail in our earlier review [12].

Drenckhan and Saint-James have elaborated on the science and mechanism behind foaming. In accordance with their study, the air is incorporated into the liquid microstructure during the aeration of beverages resulting in the formation of vapor–liquid interfaces (in-built moisture in food) having interfacial tension γ , denotes the energy $U = 4\gamma r^2$, where U is the energy input and r stands for bubble radius. One bubble requires this much (U) energy to generate, indicating that the process of producing bubbles is not a spontaneous one but rather it requires a lot of energy. In addition to these processes, bubble formation includes the production as well as rupturing the air-solvent interface, which requires a significant amount of mechanical stress. A few investigators believe that adding surface-active chemicals can increase interfacial tension [11, 13].

The science behind foaming not only involves chemical interaction among the surface active molecules but also intermolecular physical forces within bubbles which together are responsible for the stability as well as coalescence of bubbles (Fig. 1). Internal factors such as pH, ionic strength, conformation, concentration, surface tension, charge density, and physical external factors like temperature play important roles in stabilizing the foam [10]. Specific ion effects also influence bubble coalescence in liquid systems. It has been proved that the specific nature and size of an ion, polarizability, and concentration of the solution have a significant influence on the stability of foam or dispersions [14]. Foam drainage, bubble coalescence, and disproportionation or coarsening of bubbles are the phenomenon responsible for defoaming [15]. All of these destabilization processes occur simultaneously, and can thereby strengthen one another. For instance, coarsening leads to an increase in the size of bubbles by thinning the plateau border, which creates larger films resulting in quick drainage of foam [16, 17]. The bubble coalescence and thinning of intermolecular lamella can be resisted by controlling the rheology of the aqueous medium or increasing the hydrodynamic thickness of the adsorbed macromolecular layer.

A liquid's surface area, surface tension, and energy are all inversely correlated with the formation of bubbles. Furthermore, it is accurate to say that pure liquids are unable to create stable foam because they lack the minimal amount of surface area necessary for the creation of the bubble lamella or interface. It is believed that the presence of a substance

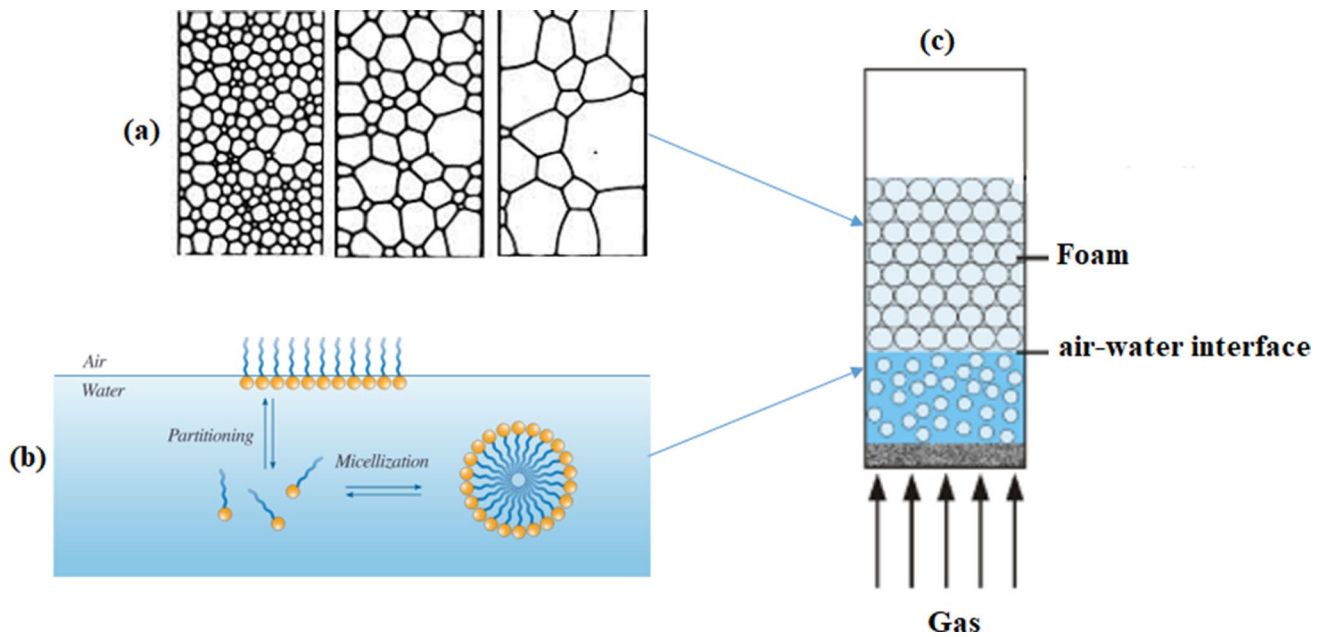


Fig.1 Mechanism of foaming (a) physics involved in foaming, (b) chemistry point of view—self-assembly of surface active components at the air–water interface, (c) science and engineering which helps gas purging for creation of foam in dynamic foam analyzer (DFA) [18–20]

with low surface tension is necessary for maintaining a stable bubble [21]. These substances can either be hydrophilic or hydrophobic in nature. According to reports, hydrophilic parts draw in water molecules, while hydrophobic parts get to engage with the bubble's gas phase. With the help of surfactants, the remaining hydrophobic components present at the interface also interact with other hydrophobic moieties, indicating that the addition of a surface active agent improves the surface activity of the interface [21, 22]. The two primary classes of biopolymers involved in stabilizing colloidal foods are proteins and polysaccharides. Soluble proteins quickly get adsorbed at the air–water interface during the formation of aqueous foam owing to their strong surface activity and capacity to create thick viscoelastic films. This results in steric stabilization of the resultant bubbles in contradiction to coalescence and disproportionation [23].

3 Foaming agents

Notably, as gas bubbles are unstable in nature, foam stability is a concerning issue. In general, liquid drainage, coalescence, and bubble disproportionation, all contribute to the instability of foams [24]. This necessitates the use of surfactants, which are surface-active chemicals that serve as stabilizers, emulsifiers, foaming agents, or foam boosters. Surfactants, which can be either natural or synthetic, are typically employed to create stable foams in beverages. Various foaming and antifoaming agents, based on their surface activity, are being used in food and allied industries; some common examples and widely used agents are tabulated in Table 1.

For instance, milk contains both high- and low-molecular-weight surfactants. Polar lipids and proteins are examples of low and high-molecular-weight surface active components respectively. These surfactants help milk foam to stay stable. As they create a viscoelastic layer at the air–liquid contact and are playing a crucial role in maintaining foam stability [25]. For stabilizing the milk foam, polar lipids such as monoglycerides, diglycerides, free fatty acids, and phospholipids adhere to the Gibbs-Marangoni mechanism, whereas milk protein prevents the coalescence of the bubble by creating a suitable barrier [26]. Additionally, the stability of foam in an aqueous medium is significantly influenced by the Ostwald ripening and gas diffusion mechanisms [27]. In the case of coffee, polar lipids and other compounds such as caffeine, chlorogenic acid, Maillard reaction products, etc. may act as surface-active compounds, which help in the stabilization of the foam [28].

In 1912, Bancroft proposed the empirical rule stating that the phase in which the surface active component is highly soluble will form the continuous phase of the emulsion, which implies that the surfactants frequently soluble in water tend to produce an oil-in-water emulsion, and those who are more soluble in oil phase tend to form a water-in-oil

Table 1 Commonly used surface active agents in food and allied industries

Surface active agents/emulsifiers	Mechanism of action/characteristics	HLB* value	Applications	References
Sodium stearoyl lactylate	Surface activity, replaces the surface lipids and, maybe, proteins as well, and helps in the stabilization of gas cells to prevent coalescence	21.0	Emulsifier, pan bread, instant fried noodles, shortening	[31–33]
Sodium dodecyl sulfate	Electrolyte ionic strength and electrophoretic mobility	40.0	Perfume, emulsifier	[34–36]
Polyoxyethylene sorbitan monolaurate (Tween 20)	Oil/water type stabilizing surfactant	16.7	Emulsifier, beverage, nanoemulsion, stabilizer	[37–39]
Polyoxyethylene sorbitan monopalmitate (Tween 40)	Oil-in-water emulsifying agent	15.6	Emulsifier, stabilizer, nanoemulsion	[40]
Polyoxyethylene sorbitan monooleate (Tween 80)	Prevents interfacial damage of protein molecules	15.0	Emulsifier, stabilizer, ice cream, nanoemulsion, biofilms	[41, 42]
Stearic acid	Helps reduce the surface tension of oils	15.0	Biodegradable surfactants, cosmetic industry	[43]
Sucrose stearate (S-1570)	Strongly improve the rheological and quality characteristics	15.0	Mayonnaise, nanoemulsion, bakery products	[44, 45]
Polyoxyethylene sorbitan monostearate (Tween 60)	Oil in water emulsifier, foam stabilizer for food, chemical and pharmaceutical preparations	14.9	Oil toppings, cake mixes, and cake icing, bio-oil emulsification	[46, 47]
Castor oil, PEG 600 and Tween 80	Co-emulsifying agent for stabilization of drug	14.0	Pharmaceutical	[48]
Polyglycerol polyricinoleate (PGPR)	Rupture the foam films by "bridging" mechanisms	10–11	Emulsifier, stabilizer for walnut oil emulsion	[49]
Lysolecithin, soya lecithin	Low molecular weight surfactants, unfolding of the proteins at the interface governs the stability of foam	8–11	Confectionary, infant nutritious products, nanoemulsion	[50–52]
Sorbitan monooleate (span 80)	Water in oil emulsifier	4.3	Bio-oil and diesel	[47]

*HLB Hydrophilic Lipophilic Balance (HLB value range: 3–6 water in oil emulsifier, 7–9 wetting agent, 8–18 oil in water emulsifier, 12–15 detergents, 15–18 solubilizers) [53]

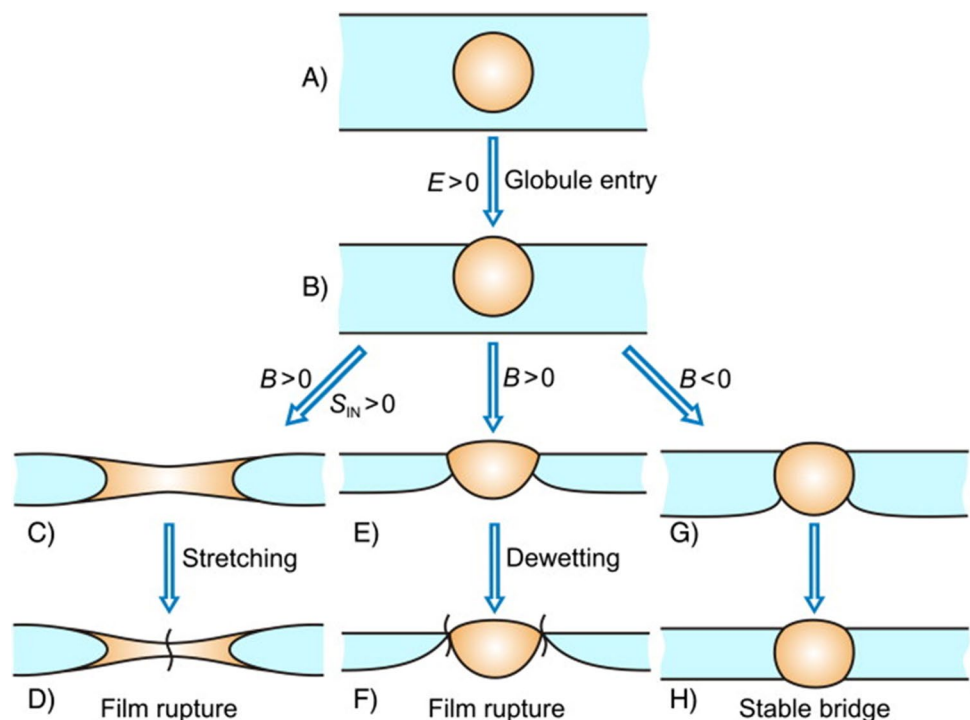
emulsion. This concept was known for a long time evidencing that hydrophilic and hydrophobic moieties affect the emulsion type [29]. Further, Griffin in 1949 proposed the concept of hydrophilic-lipophilic balance (HLB) value as a thumb rule for characterizing the surfactant [30]. The HLB value scale ranges from 0 to 20, lower-end values of surfactants indicate that the surfactant is more soluble in oil or lipid than water, and higher-end values represent more solubility of the surfactants in the aqueous phase. Emulsifiers with higher HLB numbers are used to stabilize the oil-in-water emulsion, whereas emulsifiers with lower HLB numbers stabilize the water-in-oil emulsion.

4 Antifoaming agents

Antifoaming agents are also termed foam inhibitors and defoamers. Antifoamers are used in a process to avoid foaming, whereas defoamers are utilized to remove the existing foam. Alcohols like octanol work well as a defoamer but not as antifoamers. It is now challenging to explain the antifoaming and foam-breaking effect obtained by the addition of these compounds since foam drainage and stability of liquid films are still incompletely understood. The fact that foams are created by unidentified contaminants in many industrial processes further complicates this. As a result of these factors, the mode of action of antifoaming and defoaming agents remains unclear [54].

There are different types of foam inhibitors; the first one is chemical inhibitors, which aid drainage while reducing the bulk viscosity of the liquid, and may result in less stable foam. The second type is a solubilized chemical that aids antifoaming action. In one study, defoaming has been achieved by a mix of surfactants prepared by adding tributyl phosphate and methyl isobutyl carbinol into sodium dodecyl sulphate and sodium oleate [3, 55]. Also, there are two different modes of action of antifoaming: brief fast, and slow. Fast antifoams can rupture foam films in the initial phases of film thinning; hence, in a conventional foam-stability experiment, fast antifoams entirely degraded the foaming in less than one minute. Further microscopic investigations demonstrated that such fast antifoaming agents collapse the thin layer among the bubbles by a “bridging” mechanism that involves the building of an oil bridge within the two phases of the foam (discussed in Fig. 2). Hence, such fast antifoams are desired when the foam needs to be entirely abolished. In the case of slow antifoams, they do not break up the foam until the antifoam globules have been caught and crushed via thinning walls of the Plateau borders and nodes during the foam drainage practices. Under the influence of slow antifoaming agents, various contrasting phases can be noticed during the evolution of the foam. These phases may last for minutes or hours. The final phase shows the residual long-standing foam of foam decaying [56–58].

Fig. 2 Schematic representation of oil globule at the entrance (A, B) of the foam film surface with positive entry coefficient ($E > 0$), and appropriately little entry barrier. Foam film surfaces may bridge at $E > 0$ for both positive and negative bridging coefficient (B) values. When the bridging coefficient is positive, $B > 0$, the foam film becomes unstable and is susceptible to rupturing due to bridging-stretching (C, D) or bridging-dewetting (E, F) mechanisms. The oil bridge remains stable and the foam film doesn't collapse if the bridging coefficient is negative ($B < 0$) (G, H). (With permission from Elsevier [61])



The principal component for determining whether the given antifoaming agent has a quick or slow action is the entrance barrier, which describes how challenging it is for well-dispersed antifoamers globule to access the surface of the foam. The film trapping system was used to evaluate the entrance barrier, with a threshold value of ≈ 15 Pa confirmed (which is critical capillary pressure required for drop entry), which distinguished between fast and slow antifoaming agents. Fast antifoams are defined as antifoam globules with an entrance barrier of less than 15 Pa that is capable of dissolving foam films shortly as they form, whereas slow antifoaming agents are defined as globules with an entrance barrier that prevents them from dissolving into adjacent Plateau borders. The drop entry barrier is influenced by several variables including the dimensions of the oil drops, the physiochemical composition of the oil, and the existence of cosurfactants, and electrolytes, in addition to solid particles [59, 60].

Film rupture can also happen via undissolved oil droplets accumulating on the film surface. These oil droplets either enter the air-solvent interface or spread over the film which cause displacement of the original film, and lead to rupturing of the film [3]. Figure 2 explains the mechanistic approach of oil droplets destroying the foam by the bridging-stretching mechanism and bridging-dewetting mechanism [61]. In either of these mechanisms, initially, the oil droplet comes into contact with two film surfaces, i.e. it forms a bridge among them (Fig. 2 A, B). In the bridging-stretching mechanism (Fig. 2 C, D), the oil bridge collapses, determined by the necessities of the laws of capillarity—curvature of the many interfaces, that confirms the steadiness of the capillary pressures (Laplace law), also suitable 3-phase contact angles fulfilling the vectorial balance of the interfacial tensions at the 3-phase contact lines (Neumann triangle). If this law of capillarity does not satisfy the oil bridge then it extends radially, and deformation occurs at the center of the bridge.

For the bridging-dewetting mechanism (Fig. 2 E, F), the bridge cannot deform because the surfaces of the foam layer wet the oil drop surface, which causes film destabilization at the oil bridge's circumference. Hypothetically, Garrett has demonstrated that for each of the bridging-dewetting or bridging-stretching mechanisms, the bridging coefficient $B > 0$ is necessary for the disruption of the foam layers by deformable oily precipitations. The foamed film forms a stable oil bridge for $B < 0$ without rupturing the film (Fig. 2 G, H) [54, 62, 63].

By utilizing the proper hydrophobic solid elements, oil drops, or oil-solid complexes, one can achieve effective control over particular foaming compounds (like surfactants, proteins, or soluble polymers). All of these antifoams are referred to as "heterogeneous" antifoams because the antifoam entities are spread like distinct phases in the foaming solutions [58, 61, 64]. Such heterogeneous antifoams are often referred to as "hydrophobic" antifoams; practical knowledge and theoretical study of experimental findings indicate that the surface of the dispersed units (drops) ought to be suitably hydrophobic for efficient antifoam activity [65]. To regulate foaminess and foam stability, oils and mixes of oils containing hydrophobic components are frequently utilized in a variety of techniques and consumer goods [57]. In particular cases, molecularly dispersed species (surfactant or polymeric compounds) might potentially function like foam inhibitors; they are known as "homogeneous," "molecular," or "amphiphilic" antifoams. Generally, these constituents are less effective than heterogeneous antifoams, but they possess other significant benefits such as lesser cost, no persistent stains on the finished product, food compatibility, etc. [65].

4.1 Basic requirements and characteristics of antifoaming agents

Foams and antifoams are two distinct substances with very different characteristics. A chemical additive known as a defoamer is also an antifoaming agent and lowers and prevents the production of foam in industrial processes. For instance, antifoams are emulsions containing hydrophobic particles, while foams are structures of interacting bubbles. Thus the contact between these hydrophobic particles and foam, the antifoam becomes exhausted; however, the decay in foam is fast. Numerous phenomena occur in the formation of foam and defoam. Antifoams are hence referred to as potent foam suppressors. They are crucial both from a theoretical and practical standpoint of view. Thus, defoaming and antifoaming agents are often used interchangeably. Some of the basic characteristics and requirements needed for antifoamers are given below [65, 66].

- a. Under the circumstances of the process, it should be insoluble in the foaming system.
- b. In comparison to the foaming medium, it should have less surface tension.
- c. It needs to spread out quickly in the foaming system.
- d. It must be reasonably priced or have a decent price-performance ratio.
- e. It needs to be highly effective at low dosage levels.
- f. It must be simple to handle and use (distribution in the form of a water-based emulsion or a powder),
- g. It must not be affected by process parameters (pH, temperature, water hardness)

- h. It should be inert and not have any negative effects on the manufacturing performance (no stains, reactions, or flaws in the product post-treatment).
- i. It must be safe for the environment and toxicologically, as well as approved by regulatory authorities.

5 Importance of foaming/antifoaming in food processing and allied industries

5.1 Beverage industry

Beverages with quick foaming or stable foam are very popular right now. The beverage industry is currently seeing an uptick in the usage of ready-to-use powder that can be easily reconstituted with water to create high-foaming beverages. In comparison to non-aerated beverages, these foamed beverages are more enticing to customers. Several methods including spray drying, freeze drying, mixing, agitation, etc. were used for the preparation of instant foaming soluble beverages such as coffee, tea, milkshakes, or chocolate drinks. Creamers, foaming agents, stabilizers, gums, and many such materials are widely used in the formulation of such foamed beverages [67–73]. To sustain long-lasting foam in beverages, creamers are commonly utilized as an immediate approach. Emulsifiers, proteins, or surface-active components are added to beverages to enhance the stability of the foam [74].

Many researchers have attempted to achieve the foam on the top layer of the coffee cups upon reconstitution of dried solids. Gas injection is the most commonly used method for the preparation of such desired foamed coffee [75]. Usually, air, nitrogen, or carbon dioxide are injected at a certain pressure in the liquid coffee extract followed by spray drying that results in porous structured soluble coffee powder which gives foam upon dissolving in water [76–78]. In one study, the porous soluble coffee powder produced by spray drying was mixed with a molten frozen coffee extract which exhibited agglomeration and sticking of porous particles in the molten matrix. Further, this mixture was freeze-dried. The obtained instant soluble coffee powder produced 1–2 mL of foam when 5 g of coffee powder was dissolved in 200 mL of water at 90 °C [79].

5.2 Fermentation

According to a broad definition, foam develops if a gas–liquid distribution has a gas holdup of more than 90%. In industrial applications, foam is typically an undesirable by-product because foam makes it difficult to control the process and handle the equipment. Foam is therefore a major problem for the fermentation industry since it can result in the loss of culture fluid and cells, accelerate cell lysis, cause environmental contamination, and restrict the transfer of oxygen. These factors make foam prevention and/or management very important [80]. According to Ghosh and Pirt, foaming can have highly negative effects on fermentation if it is not controlled. Although foaming issues are process-specific, they can occasionally be so severe that to control them several foam probes (generally used in fermenter and bioreactor) installations are necessary [81].

Though the presence of foam can negatively affect a bioreactor's efficiency, the majority of cell cultures produce foam stabilizers such as proteins, sugars, or biosurfactants. Hence, antifoams are necessary to efficiently produce penicillin, yeast, enzymes, lactic acids, or bioethanol through fermentation by controlling gas evolution throughout the procedure. One must be extremely careful in selecting the antifoam and its dosage to prevent detrimental effects on oxygen transfer, the metabolic growth rate of microbes, and the consecutive purification stage such as in the downstream ultrafiltration stage, where the antifoaming agent might potentially foul the membranes. Usually, in current yeast manufacturing plants, the antifoams are incorporated via automated electrode-activated systems. In this implementation, silicone-based oils and emulsions, polyoxy-alkylene polymers and ester derivatives, natural oils like soybean oil and lard oil, or blends of them are used as the antifoaming agents. Apart from them, various novel antifoaming agents such as fluorocarbon – hydrocarbon unsymmetrical bolaform are progressed in recent years, which are found to be more effective in terms of cost, and efficient at low dosage levels compared to commercial antifoaming agents generally used to control the foam in the fermentation industries [57, 65, 82]. Their ability to form foam is limited, and they are less sensitive to changing the ionic strength of the aqueous subphase than classical ionic surfactants. However, their limiting surface tensions are relatively high; their critical micelle concentration (CMC) values are higher than those of the classical ionic surfactants, which have a similar hydrophobic driving force for adsorption [82, 83].

5.3 Enzyme purification

Loss of enzyme structure and its catalytic activity are the main concerns of enzyme downstream processing. Adsorptive bubble separation or foam fractionation is an alternative strategy for the efficient purification of enzymes. The principle of preparative foaming was developed way back in 1920. Foam fractionation is one of the separation methods which utilizes an aqueous foam as the medium [84]. This technique utilized foam characteristics such as lower water content and higher particular surface area to resourcefully enhance enzymes and proteins from aqueous solutions [85]. It involves the adsorption of surface-active substances to the gas–liquid interface by passing gas through the broth containing the enzyme molecules. The gas phase is stabilized by the bipolar molecules through the formation of cohesive films. Hydrophobic portions are attached to the gas medium while the hydrophilic portions are inclined to the liquid medium. The foam rises in a column, though drainage and coalescence decrease the foam as the excess liquid flows back. Thus, the foam phase becomes rich in enzyme molecules. Non-adsorbed compounds are collected as retentate [86–88]. The foam obtained in the last part of the column is liquefied by ultrasonication or stirring.

Foam fractionation of enzymes is governed by protein concentration, phases of foam, adsorption of surface-active components at the interface, foam structure, foam stability, pH, dimensions of the foaming device, and its hydrodynamic aspects like bubble size, superficial gas velocity, etc. Based on their hydrophobic characteristics, the target components in foam fractionation adsorb on the surface of the rising bubbles and are subsequently gathered in the foam [89]. For example, the foam fractionation process was used for the purification of laccases from *Cerrena unicolor* and *Pleurotus sapidus* under different physicochemical conditions. Surfactants like Cetyl Trimethyl Ammonium Bromide (CTAB) and Polysorbate 80 were used in the range of 0.2 mM to 1.5 mM. The process was carried out for a range of pH from 3 to 10. pH 4 was the isoelectric point of the enzymes. It was observed that the source of the enzyme is important based on partitioning efficiency in the foam fractionation method. Laccase synthesized by *Cerrena unicolor* provided a yield of up to 50% at pH 7.5 and 0.5 mM concentration of CTAB (cCTAB); whereas, laccase from *Pleurotus sapidus* revealed partitioning coefficients of up to 8 with 25% yield at pH 4 and cCTAB = 0.5 mM [90]. In a recent study, foam fractionation was effectively used downstream of β -lactamase with 70% catalytic activity.

Thus, foam fractionation of enzymes is a promising technology applicable for both lab and industrial scales. However, various parameters governing process efficiency need to be optimized and controlled for efficient purification including pH, temperature, water hardness, surface tension, surfactant concentration, etc. [91].

5.4 Protein separation

As previously mentioned, the hydrophobicity of the air–liquid interface in the process of foam fractionation of proteins causes a release of hydrocarbon chains hidden within protein complexes with partly unfolded structures, helping their adsorption at the interface [92]. The protein's natural structure is preserved at the interface, which encourages the development of new bonds in the unfolded protein molecules even though it can disrupt certain non-covalent or covalent interactions. Furthermore, some adsorbed protein elements fail to recover their original configurations after desorption from the interface [93]. Sometimes, the ineffective separation, causes proteins to lose a large amount of their bioactivity, especially enzymes and therapeutic proteins in foam fractionation. It is crucial in this circumstance to limit foam-induced protein denaturation throughout foam fractionation.

In comparison to conventional protein separation techniques, foam fractionation has the potential to be less expensive, but it also has some limitations. One of the limitations is that not all proteins when aerated at low quantities produce a foam layer. The other is the potential denaturation of proteins brought on by foaming [94]. The majority of the existing methods (ultrafiltration, gel filtration, ion exchange, precipitation, and coagulation) used to separate dissolved or dispersed components from an aqueous stream are time-consuming, costly, and difficult. Whey protein concentrates (WPC) and isolates are being produced on a large scale using membrane filtration techniques at a pace of more than 1×10^5 MT annually. Although the process of foaming may cause proteins to unfold, it can be stopped by using alternative strategies. It has been found that foam fractionation is a beneficial technique for either concentrating proteins from diluted whey solutions or lowering the protein content of waste solutions. At an initial whey concentration of 500 $\mu\text{g}/\text{mL}$, and a gas flow rate of 290–300 mL/min at pH 5.0, the approach was discovered to be more efficient. Bubble diameter increased as the surface gas velocity increased, and there were more bubbles produced overall resulting in increased interfacial area, and immediate adsorption of the protein [95].

6 Foaming and antifoaming during processing

Foam control in industry is yet an experimental work. The process of foam control best suited for one plant for any specific process is not always effective for similar processes in other plants. The plan and working constraints of a bioreactor may influence the properties and degree of foam formation. Hence, improper types and dosages of anti-foaming agents should be treated with caution. The selection of suitable antifoaming compounds should be dealt with a proper understanding of the process. A universal set of guidelines for efficient antifoaming during the process cannot be developed since the economic considerations influencing the selection of the antifoaming compound differ from plant to plant.

The minimal amount required, the maximum yield of the product, or the absence of any antibacterial action, are often the key factors that determine an antifoaming agent's effectiveness. For the separation of enzymes that are catalytically active, foaming is a quick, gentle, environment-friendly, and economically advantageous technique. It has the potential to be an important part of creative purification techniques, both in the lab and in large-scale manufacturing. Foaming needs to be adjusted for each target enzyme because of many factors that influence the process, for example, the correct protein content, superficial gas velocity, as well as other variables should be adjusted according to the process [88].

6.1 Methods of controlling foam

Many manufacturing processes, such as chemical and fermentation processes, are prone to foam production. In some operations, like the brewing of beer, its generation is a desired quality. In biochemical processes foam controlling is one of the important operations, especially during fermentation. Controlling foam is crucial since it hampers a variety of processes that result in material loss through the exhaust lines, contamination of the fermentation batch, and environmental hazards. Incorporating antifoam compounds is the recommended way of controlling foam in fermentation, while occasionally a mechanical foam breaker is employed in addition to the chemical antifoam. Efficient foam management with a lower cost has a significant impact on the economics of the process because controlling foam in fermentations is an expensive and inefficient operation [96].

There is a wide range of chemical formulations that can be utilized to either stop foam from forming or eliminate it once it has already formed. The majority of foam-dispersing substances can perform both functions. The defoamer or antifoam agent is created precisely for a particular application, and the global market for these fundamental ailments is worth billions of pounds annually. Insoluble oils, polydimethylsiloxanes, and other silicones, certain alcohols, stearates, and glycols are often used as antifoaming compounds. There are physical, chemical, and mechanical methods generally used for defoaming operations at the industrial level (Table 2). Ultrasound, thermal, or electrical treatment are meant to be used as physical techniques for reducing foam. Liquid sprayers, centrifugal foam breakers, and orifice foam breakers are typical mechanical techniques for breaking foam [97]. Researchers have reported no decrease in the number of cells after ultrasonic treatment [80, 98], but later it was observed that all physical ways of managing foaming are occasionally inappropriate for fermentations. Cells may get adversely affected by physical techniques used to prevent foam [66].

Unwanted foams are typically unavoidable during the food processing process. They may cause product loss by physical means, thermal damages, equipment fouling, oxidation, or poor product appearance due to product cavities or discoloration [99]. Recently, airborne ultrasonic vibrations are found to be effective in suppressing the foam. It has been observed that the structures of foams of pre-mixed alcoholic beverages and carbonated soft drinks can be effectively destroyed by airborne ultrasound with the help of high intensity of ultrasound [100, 101].

7 Recent advances in foaming and defoaming agents in vegan foods

In some of the earlier research on foam management, whether in the treatment plant or oil recovery stages, the environmental risk that the foaming and defoaming agents cause was hardly ever taken into account. Many antifoams and defoamers contain harmful components, although oil extracts utilized in the making of defoaming and antifoaming agents are derived from natural plant resources. Rarely the available literature provides in-depth investigations on the characterization of plant oils from soybean, pecan nuts, palm kernel, coconut, groundnut, walnut, tiger nut, and castor nut to examine their applicability as defoamers and antifoams [110].

Table 2 List of different methods of controlling foam formation

Sl. No	Foam controlling methods	Mechanism	Industrial effects	Reference
1. Physical methods				
a.	Thermal foam breakers	Heating and cooling the foam; expansion and compression of the bubbles that result in their destruction, reduction in surface elasticity	Practical difficulties, energy consumption, and the effects of high temperatures on the product	[101, 102]
b.	Electrical foam breakers	Forces created by an electric current on liquid and gas when they pass through the foam	Very limited application hardly used method	[80, 103]
c.	Mechanical foam breakers	It collapses the foam bubbles by mechanical shocks created by centrifugal, compressive, impact or shear forces, suction, or pressure changes	Greater and more widespread use; high running cost, significant scaling-up problems frequently arise, complicated designs	[80, 104, 105]
d.	Ultrasound	It uses high-intensity ultrasonic waves for defoaming. A potential and promising method for the food, chemical, and pharma industries Considered a clean technology	Significant de-bubbling, about 80–90% of the bubbles in the range of 100 μm , and of 40–60% of bubbles with a diameter near 250 μm was observed Very noisy operation, higher air generation capacity, controlled airflow, contamination, and energy consumption	[101, 106, 107]
2. Chemical methods				
a	Sunflower oil, oleic acid, sperm whale oil, soap stock from plant oil; synthetic compounds such as silicone, polypropylenes, and synthetic fatty acids	Interrupt the surface around the gas bubbles, destabilizing bubble walls so that the bubble can break and release the trapped gas	Antifoam chemicals can be used effectively to defoam products when chosen properly, but they can also have major negative effects on the contamination of the product	[108, 109]

In such a scenario, plant-based gums and stabilizers that exhibit foaming, emulsification, and gelling properties are being used in new trending vegan products. Polysaccharide gums represent one of the most important raw ingredients and became a part of deep research due to their sustainable, biodegradable, and eco-friendly nature. It has been a well-documented phenomenon about natural gums that they form 3D interconnected molecular networks (gels). The strength of such 3D gels depends upon the polysaccharide's structure, concentration, solubility, pH, temperature, ionic strength, and solvent nature. The linear polysaccharides occupy more volume than branched ones which accounts for higher viscosity at the same concentration. Hence they are found to be a good swelling agent. Also, they hold large amounts of water between their chain and branches. Due to their structural and functional characteristics, they are widely used for multiple applications [111]. In espresso coffee, the presence of polysaccharides helps in improving the viscosity, thereby stabilizing the foam [112].

Conventionally egg protein and milk proteins especially whey protein isolate, whey protein concentrates, and skim milk powder are used as a foaming ingredient as well as a stabilizer in a variety of aerated food products. Their foaming characteristics and physiochemical properties have been determined in detail [113]. It has been observed that plant protein exhibit relatively poor functional and physiochemical properties compared to egg and milk proteins. But nowadays plant proteins are gaining more popularity, as they are more sustainable than milk and egg protein [114]. Further, to improve the functional parameters of plant proteins such as solubility, molecular flexibility, surface charge, and surface hydrophobicity, physical, chemical as well as enzymatic methods have been developed and more research is focused on using these plant-based proteins as a foaming ingredient in different food applications. Figure 3 explains the overview of plant proteins and the factors responsible for their functionality [115].

8 Conclusion and future remarks

Foaming is always a concern in industrial processes, especially for the chemical and food industries. Modern foam management techniques are being utilized to reduce the influence of foam in industrial applications. It has been observed that the ultrasonic defoaming technique is promising to control the foam in food, chemical, and pharmaceutical segments;

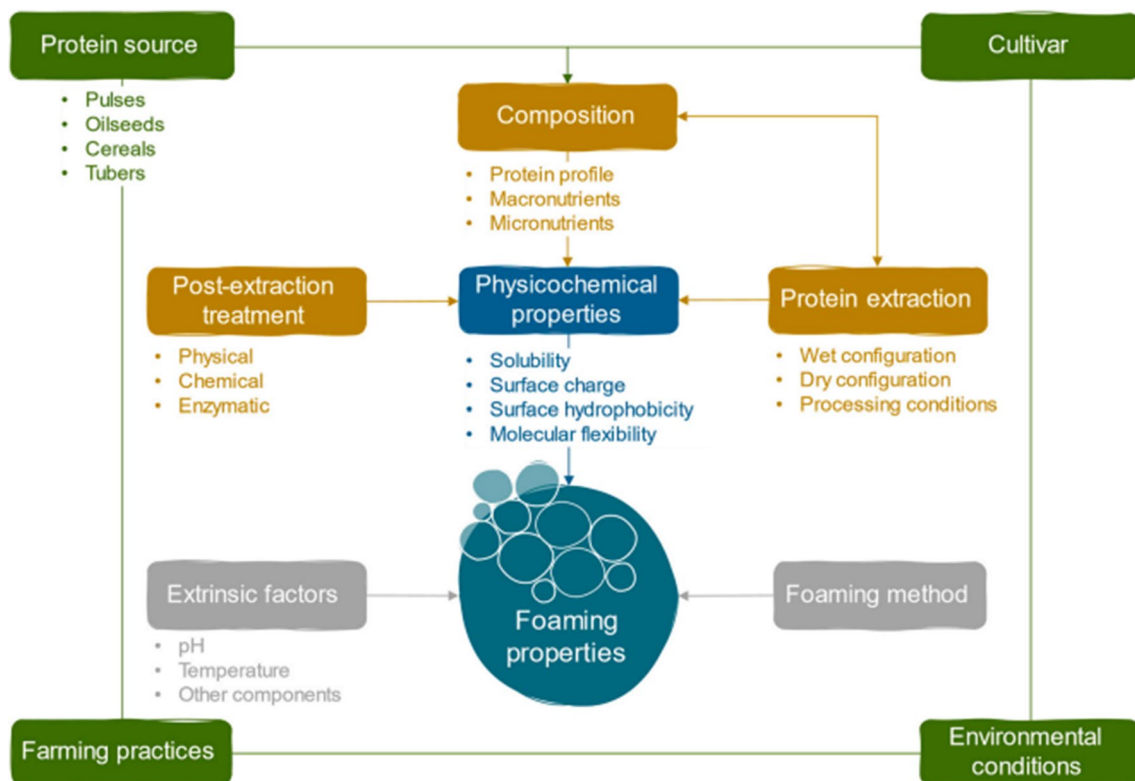


Fig. 3 Overview of plant proteins and factors responsible for their functionality (with permission from Elsevier [115])

however, for such a system, some specific parameters like frequencies and power, for particular food applications, need to be optimized. Whereas, in upstream applications of bioprocesses, foam formation is frequently observed. Established methods for preventing and removing foaming in a bioprocess primarily depend on chemical techniques, while mechanical and physical techniques are also employed. Chemical treatments can both prevent foam from arising and remove the existing foam, but mechanical and physical approaches can only eliminate existing foam. Machine vision-based techniques are good choices to detect the development of foam because foam is a crucial bioprocess factor that can be visually recognized. This might be enhanced by additional study by mathematical models that are independent of processes, and by standardizing the recording and evaluation of empirical parameters. This would eventually lead to a more widespread application of foam separation at bigger scales.

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Declarations

Competing interests The authors declare no competing interests.

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