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Microbubbles in Food Technology

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Abstract

Microbubbles are largely unused in the food industry yet have promising capabilities as environmentally friendly cleaning and supporting agents within products and production lines due to their unique physical behaviors. Their small diameters increase their dispersion throughout liquid materials, promote reactivity because of their high specific surface area, enhance dissolution of gases into the surrounding liquid phase, and promote the generation of reactive chemical species. This article reviews techniques to generate microbubbles, their modes of action to enhance cleaning and disinfection, their contributions to functional and mechanical properties of food materials, and their use in supporting the growth of living organisms in hydroponics or bioreactors. The utility and diverse applications of microbubbles, combined with their low intrinsic ingredient cost, strongly encourage their increased adoption within the food industry in coming years.

INTRODUCTION

Microbubbles are small bubbles typically 0.1 to 100 μm in size. They are small enough to have distinctive physicochemical properties that can be exploited for the design of effective and environmentally friendly food technologies. For example, microbubbles shrink and collapse in the surrounding liquid because of the fast gas dissolution rate driven by their large internal pressure. Collapsing microbubbles create powerful shock waves and high-speed liquid jets that can be used to remove fouling material from food processing surfaces and pieces of equipment.

Microbubble collapse also promotes the formation of highly reactive chemical species, such as hydroxyl radicals, which can effectively disrupt biofilms and help remove pesticide and contaminant residues from fruits, vegetables, and other food products. Traditionally, cleaning of processing equipment and sanitizing of food surfaces require the use of chemical cleansers and copious amounts of water to rinse the chemicals away. The use of microbubbles could help reduce or eliminate the need for those chemicals and decrease water usage.

Microbubbles have a myriad of other food applications. For example, their large collective surface area and rapid dissolution rates make them efficient carriers of gas sanitizers (e.g., ozone) or oxygen for use in hydroponic and vertical farms. When introduced into the food matrix, they can improve the functional properties of food materials such as proteins. And when provided with a suitable stabilizing shell, microbubbles can be used to imitate the creamy mouthfeel of fat in dietary foods.

In this review, we survey a range of established and emerging food applications in which the properties of microbubbles play a key role. Microbubbles can provide safe, effective, and clean technologies with great potential for industrial adoption. We observe that further theoretical and experimental studies are needed to fully exploit the potential of microbubble technologies in the food industry. Specifically, this can be addressed by studies addressing the fundamental physics involved and developing approaches for cost-effective generation of well-controlled microbubbles.

GENERATION OF MICROBUBBLES

The generation of microbubble dispersions requires considerable energy to overcome the surface tension forces at the gas–liquid interface opposing the growth of the emerging gas phase. Various methods are used to generate microbubbles in food technology, typically involving the application of acoustic or hydrodynamic energy. These include decompression, Venturi generators, ultrasound, and swirl flow.

Decompression

Decompression is a common generation method in which microbubbles are formed by the spontaneous separation of gas dissolved in supersaturated water after a sudden drop in hydrodynamic pressure. In food applications, water is typically saturated with air at several atmospheric pressures (0.3–0.6 MPa) and then injected into a tank through a decompression nozzle. As the saturated water decompresses, the dissolved gas desorbs and nucleates a myriad of microbubbles to reach a more favorable thermodynamic state at the lower pressure conditions (Rodrigues & Rubio 2007, Zheng et al. 2015).

Decompression methods also generate microbubbles by cavitation (nucleation of vapor in liquids) if the pressure in the decompression region drops to the appropriate value of the water-vapor pressure. Cavitation bubbles may contain both water vapor and some desorbed air, but much of the vapor condenses as the pressure recovers away from the decompression region. The level of initial liquid saturation influences the extent of air desorption and, therefore, the size and number of the

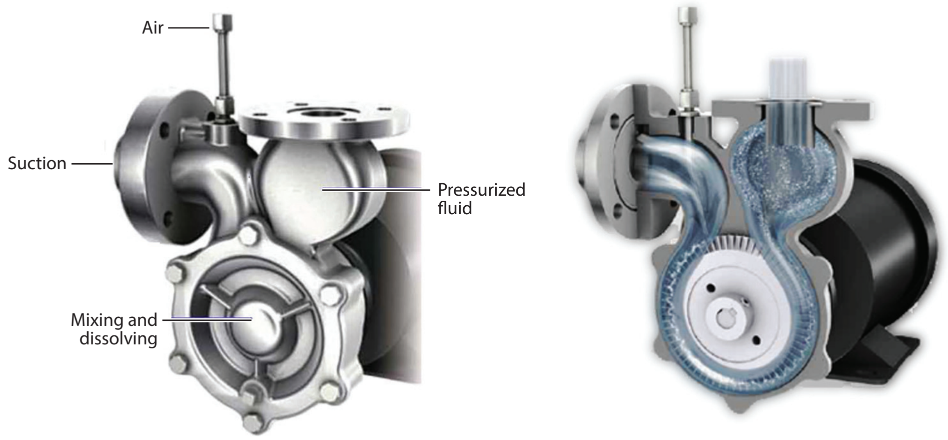

Figure 1

Multiphase pump for microbubble generation. Air drawn into the suction chamber of the pump is mixed with water, partially dissolved, and pressurized using mixing blades. Figure adapted with permission from Nikuni Co. Ltd.

generated microbubbles. High saturation levels, for example, increase the number of nucleation events and the amount of air in the nucleated bubbles, which in turn increase both the number density, which is on the order of 10^{10} m^{-3}, and the average size of the microbubbles, which is on the order of 10 μm (Maeda et al. 2015, Oikonomidou et al. 2018).

Several methods can be used to reach the desired level of fluid saturation. For example, water and compressed air can simply be mixed or agitated together in a pressurized tank (Parmar & Majumder 2013). Alternatively, multiphase centrifugal pumps can be used for more efficient generation, eliminating the need for air compressors and saturation tanks. Air is continuously drawn into the suction chamber of the pump as water flows into the equipment, enhancing dissolution and generating sufficiently high operating pressure (**Figure 1**). By tuning the parameters of the system, decompression methods can generate very fine bubbles (smaller than ∼50 μm) with high bubble number density and flow rate, making this method particularly attractive for applications such as flotation of contaminants and cleaning of processing surfaces (Maeda et al. 2015, Etchepare et al. 2017).

Venturi Generator

Figure 2 illustrates the operation of a Venturi microbubble generator. Millimetric bubbles enter the converging section of a Venturi tube, drawn by the low hydrodynamic pressure originating from rapid liquid flow (Thang & Davis 1979). The bubbles then suffer rapid deceleration and severe fragmentation in the diverging section and are carried downstream as a fine dispersion by the liquid flow (Fujiwara et al. 2007, Huang et al. 2020, Zhao et al. 2019). Bubbles can also be nucleated by hydrodynamic cavitation if the pressure at the converging section of the Venturi tube is sufficiently low (Pawar et al. 2017). In a common variant (ejector-type generator), bubbles are entrained into the generator by a fast liquid jet introduced through an ejector at the throat of the Venturi tube (Gourich et al. 2007, Haidl et al. 2021).

Venturi generators have no moving parts, are reliable and simple to operate, and can generate high bubble number density with low energy consumption. The size and number density of the generated microbubbles depend on the liquid flow rate and the generator design, especially

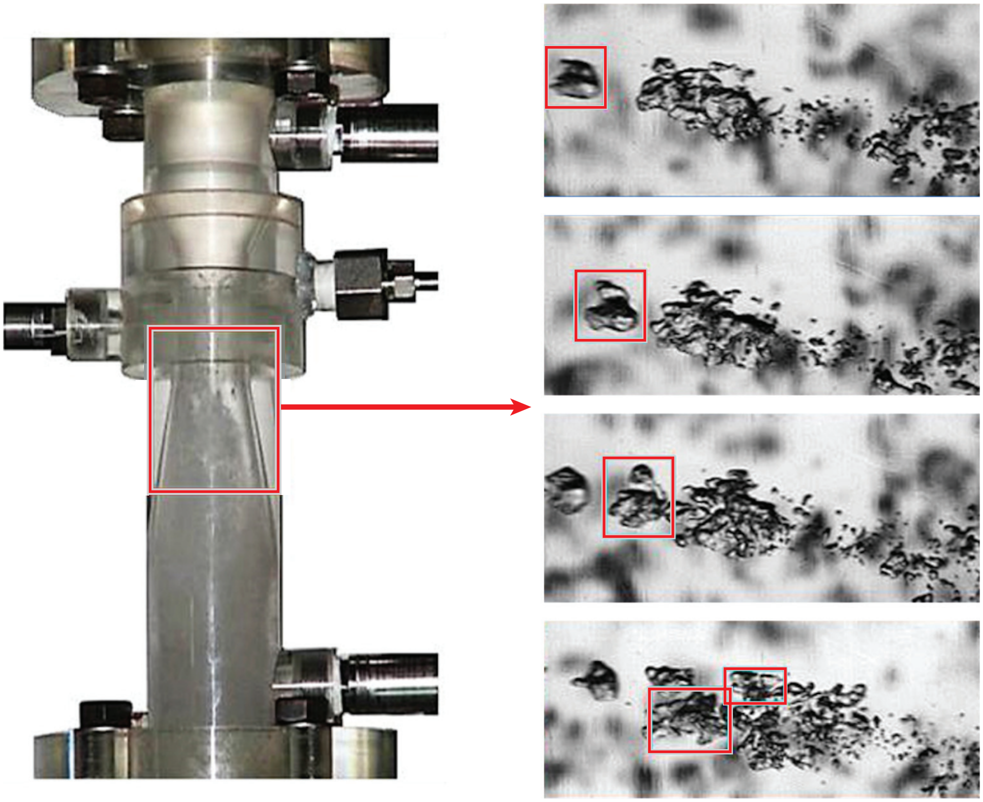

Figure 2

Bubble fragmentation at the exit of the throat (*red box*) in a Venturi microbubble generator. Figure adapted with permission from Zhao et al. (2017).

the opening angle of the diverging tube section (Huang et al. 2020). Higher liquid flow rates induce lower pressure at the converging section of the tube, driving more gas into the liquid and increasing the bubble number density (Sakamatapan et al. 2021). Higher flow rates also generate more rapid deceleration, pressure waves, and turbulence in the diverging section, causing more severe fragmentation and leading to smaller bubbles (Sakamatapan et al. 2021). Similarly, a larger opening angle decelerates the flow more rapidly and generates finer, although less uniform, microbubble dispersions (Lee et al. 2019). The combined influence of fluid properties, flow conditions, and tube configurations is frequently discussed in the form of dimensionless, often empirical correlations, some of which have been recently summarized by Huang et al. (2020). For instance, the average diameter d of the bubbles generated in the Venturi tube in relation to the diameter of the Venturi throat D scales approximately as a weak power law $d/D \sim Oh^{-0.6}$ $Re^{-1.1}$ of the dimensionless liquid Ohnesorge number Oh and the dimensionless Reynolds number Re based on the diameter of the Venturi tube throat (Huang et al. 2020).

A better understanding of the mechanisms of bubble fragmentation (Li et al. 2019, Sakamatapan et al. 2021) and the support of realistic computational fluid dynamic models (Jensen et al. 2020, Sharma et al. 2018, Simpson & Ranade 2019) have recently motivated a series of new designs. For example, Lee et al. (2021) developed a two-dimensional Venturi generator in which the opening angle of the diverging section is not constant but changes in the axial direction. The rate of change of the opening angle is designed to improve the interaction between the entrained bubbles and the more energetic central flow to optimize bubble breakup. Multistage and combined generation mechanisms have also been employed to enhance generator performance. Ding et al. (2021) developed a two-stage generator in which a second Venturi tube in series intensifies the breakup mechanism to reduce the bubble size to the submicrometer scale, and Wu et al. (2022) and C. Li et al. (2022) reported better generator performance by inducing high-speed swirling flow in the Venturi tube.

Ultrasound

Ultrasound devices generate microbubbles via large-amplitude waves (power ultrasound) and frequencies between 20 kHz and a few hundred kilohertz (Kentish & Feng 2014). In the food industry, power ultrasound is often generated using acoustic transducers, which apply an inverse piezoelectric effect to transform electrical energy into acoustic oscillations (Dion 2011, Gogate & Pandit 2015).

Ultrasound creates low- and high-pressure waves in a liquid, and sufficiently powerful ultrasound can generate microbubbles by inducing cavitation during the low-pressure period in the sound wave (Mondal et al. 2021). The average bubble radius r can be roughly estimated by a simple relation $r = 3/F$, where F is the ultrasound frequency (Kentish & Feng 2014). Ultrasound also generates microbubbles by gradually increasing the size of interstitial gas pockets through a process known as rectified diffusion. In a pulsating gas pocket, more gas enters through the larger surface area during expansion than leaves through the smaller area during compression, gradually increasing the amount of gas in the pocket (Crum 1984, Lohse 2018).

Depending on the bubble size, the response of the generated microbubbles to the pulsating field can be highly nonlinear, particularly near the bubbles' resonance frequency. Vibrated by ultrasound, microbubbles can resonate in a process known as inertial cavitation. During this process, microbubbles can grow to more than twice their original size during the low-pressure period and then collapse during the high-pressure period due to the large inertia of the surrounding liquid (Mondal et al. 2021). These collapsing bubbles generate powerful shock waves, high-temperature spots, and strong hydrodynamics stresses, which can help inactivate microorganisms and remove hard fouling materials from food processing surfaces (Burfoot et al. 2017, Ehsani et al. 2022).

Swirl Flow

Swirl-flow generation is a well-established method to generate microbubbles via bubble breakup by liquid vortices and turbulence. In these generators, hydrodynamic shear induced by a high-speed rotating liquid makes macroscopic gas bubbles first stretch and subsequently pinch off, in the process generating a cloud of microbubbles. The rotating flow is created by pumping the liquid through helical flow channels or by introducing it tangentially in a cylindrical mixing chamber, as illustrated in **Figure 3**. Gas and liquid flow rates are key operational parameters. Increasing the gas flow rate typically increases the microbubble size, whereas increasing the liquid flow rate decreases bubble size by accelerating the rotation speed and increasing shear (Mawarni et al. 2022). This generation method enables simple design and the ability to generate fine bubbles, often at a lower cost than sonication and decompression methods (Kawahara et al. 2009, Li & Tsuge 2006, Ohnari 2000).

Researchers are continuously working to improve generator designs. Recent progress has been driven by the availability of new fabrication methods such as additive manufacturing and the use of high-fidelity computer simulations for mechanistic understanding. For example, Kim et al. (2019) developed an innovative 3D-printed design that combines helical channels to induce swirling flow

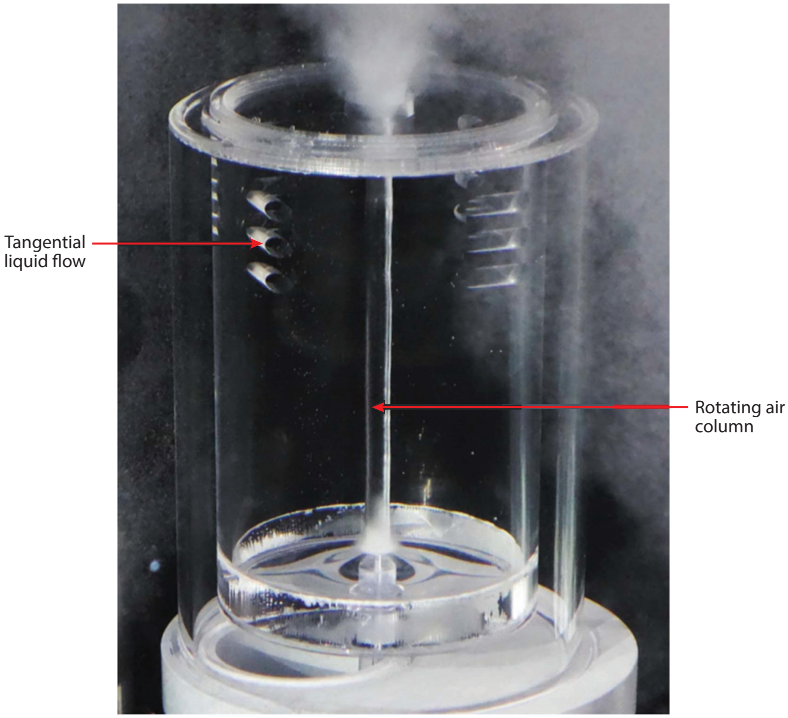

Figure 3

Formation of microbubbles in a dual-chamber, dual-vortex swirl-flow generator. Figure adapted with permission from Takohgiken Co. Ltd.

and a central tube in the axial direction to introduce compressed air. Large velocity gradients develop when the swirling flow and the axial flow mix in an upstream discharge nozzle, inducing strong shear and efficient bubble breakup to sizes in the 10–100 μm range. However, the approach can be a disadvantage in applications where high bubble density is required because exceeding a threshold air flow rate results in enhanced coalescence, which in turn leads to large bubbles and reduced bubble number density.

The issue of bubble number density has been addressed in recent designs that combine the high-density bubble nucleation of conventional Venturi generators with the enhanced bubble fragmentation by vortices and turbulence of swirl-flow generators. X. Wang et al. (2020, 2021) proposed a combined design that incorporates swirling flow into a Venturi microbubble generator by introducing the liquid tangentially into the mixing Venturi chamber. Using high-fidelity simulations, these researchers identified additional bubble breakup modes that result from the combined design, which enabled the generation of smaller microbubbles and higher number densities than those from a conventional Venturi generator.

APPLICATIONS OF MICROBUBBLES IN FOOD SYSTEMS

Owing to their small diameter, microbubbles are finely dispersed throughout a product with a very large contact area in relation to their volume (specific surface area), enhancing the activity of the dispersed gas phase. Interaction of the bubble interface with fouled surfaces or biofilms confers desirable cleaning and disinfecting properties. When dispersed in food matrices, microbubbles reduce bulk density while also demonstrating physical behaviors typical of colloidal suspensions, including rheological contributions or partial replacement of fat content. Efficient delivery of oxygen to plant tissues and cultivated cells is also a promising application for hydroponic farming as well as cellular agriculture.

Cleaning of Processing Surfaces

Cleaning of processing surfaces and pieces of equipment is essential in the food industry. Such operations often require harmful chemical cleansers and substantial amounts of water to rinse those chemicals away. The use of microbubbles as a cleaning agent may offer an environmentally friendly alternative to ensure food safety and maintain peak equipment performance.

Much of our understanding of the ability of microbubbles to clean processing equipment comes from studies that aimed to reduce the use of chemicals to clean separation membranes. Membranes provide an economical way to accomplish various separation operations in the food industry, but fouling is a serious problem that rapidly limits transmembrane flow and reduces the selectivity and performance of the separations (Xu et al. 2020). Early research by Agarwal et al. (2012, 2013) studied the potential of air microbubbles to remove biofilms from separation membranes without using chemicals. Promising results showed approximately 20% more biofilm detachment after the membranes were exposed to a dispersion of microbubbles for 1 h in comparison to traditional chemical cleaning with sodium hypochlorite for 2 h (Agarwal et al. 2012). Other results, however, also showed that the cleaning efficacy varied widely with not only the type of foulant but also the age of the biofilm, with better cleaning observed for biofilms in the late stationary phase (Agarwal et al. 2013, Watabe et al. 2016).

Microbubbles are now commonly employed to clean membranes used to remove contaminants from wastewater (recently reviewed in Arefi-Oskoui et al. 2019) and to prevent fouling by reducing direct contact between the foulant and the membrane surface (Levitsky et al. 2021, Y. Wang et al. 2021). Studies on membranes used to separate liquid foods, however, remain scarce. Results from these studies showed that cavitation microbubbles represent an effective means of breaking concentration polarization and removing foulants from membrane surfaces, with the caveat that most studies were limited to membranes for the processing of milk and other dairy products (Chanukya & Rastogi 2017, Gao et al. 2014, Heikkinen et al. 2017). Parameters such as pH, temperature, cross-flow velocity, and transmembrane pressure affect cleaning efficacy, as discussed by Muthukumaran et al. (2005) and, more recently, by Aktij et al. (2020) and Córdova et al. (2020), but generalization across treatments is difficult due to the disparity among experimental conditions. Key operational parameters such as cleaning time and ultrasonic intensity substantially enhanced cleaning efficacy; however, they must be tightly controlled both to avoid cavitation wear that reduces the life of the membranes and to maintain acceptable energy costs (Aktij et al. 2020, Levitsky et al. 2021, Masselin et al. 2001, Muthukumaran et al. 2006). The economic aspects of these operations have been comprehensively reviewed by Aktij et al. (2020). Cost models suggest that operational costs are directly proportional to ultrasound power and sonication time and that, in some conditions, ultrasound operations may decrease costs by reducing extra pumping energy induced by membrane fouling.

Microbubble dispersions are also useful for removing biofilms and hydrophobic foulants, such as oils, fats, and grease, from processing surfaces. For example, Burfoot et al. (2017) found that adding air microbubbles smaller than ~50 μm into the cleaning water improved the removal of biofilms from stainless steel surfaces and polypropylene pipe walls by approximately a factor of 10. Similarly, microbubble dispersions with bubble size between ~30 and 60 μm (in deionized water) removed more than 80% of oil from metallic parts in approximately 15 min with lower power consumption than ultrasonic cleaning (Tan et al. 2020). More recently, Chung et al. (2022)

reported that microbubble dispersions added to clean-in-place treatments can increase the removal of milk-fat deposits from the stainless-steel surface of heat exchangers by up to 30%.

Hybrid methods that combine microbubbles and more traditional cleaning methods, such as chemical sanitizers, surfactants, and shear, are also a fertile ground for development. In combination with a low concentration of sanitizers, cavitation microbubbles were found to fully remove *Listeria monocytogenes* (with added 0.5 ppm ozone) and *Escherichia coli* biofilms (with added ~1 ppm chlorine) from stainless steel surfaces with cleaning treatments shorter than 60 s (Baumann et al. 2009, Zhou et al. 2012). In addition, recent experiments on oil-coated steel surfaces (P. Li et al. 2022) showed that the combination of ultrasonic treatment and microbubble dispersions provided up to 50% greater cleaning efficiency than the ultrasound treatment alone.

The cleaning ability of microbubbles in treatments involving cavitation is attributed largely to the generation of shock waves and high-speed microjets during inertial bubble collapse (Jin et al. 2022, Tanimura et al. 2010). Microjets are generated when microbubbles collapse near a solid surface. During this asymmetric collapse (**Figure 4*a*,*b***), the bubble interface folds inward, forming a fast-moving liquid jet directed toward the surface (Brennen 2014, Ohl et al. 2006, Wang & Manmi 2014). During the brief period in which the jet impinges the surface, the flow exerts strong shear stresses that can locally clean the surface (**Figure 4*c*,*d***). Shock waves are also emitted during the inertial collapse of the microbubbles and help disrupt and remove contaminants

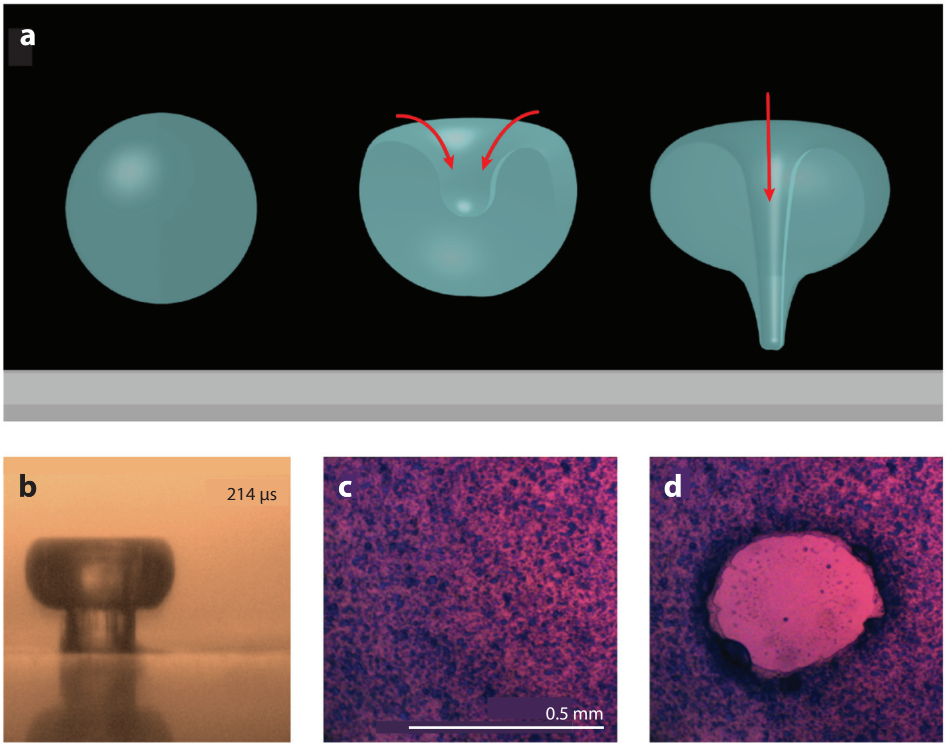

Figure 4

(*a*) During microbubble collapse near a solid surface, the bubble interface folds inward (*red arrows*) and generates a high-speed liquid jet directed toward the surface. (*b*,*c*,*d*) Liquid jets emitted during the collapse of the microbubbles help disrupt and remove contaminants. Figure adapted with permission from Ohl et al. (2006).

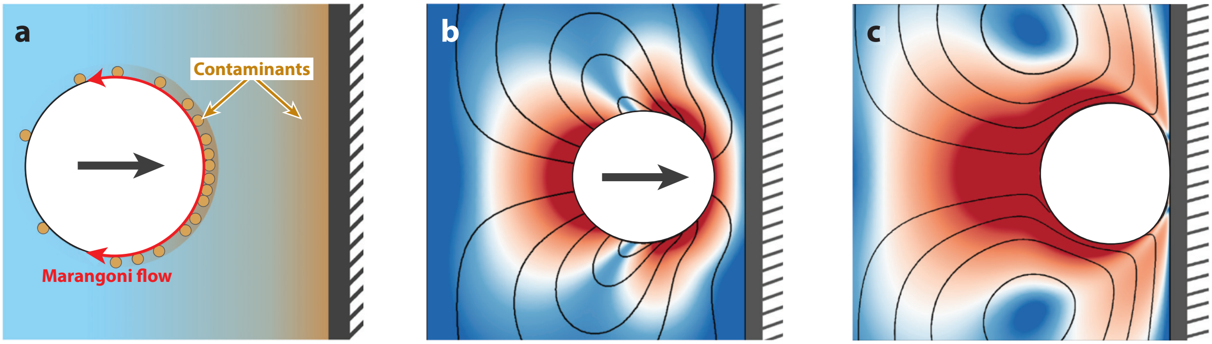

Figure 5

Microbubbles spontaneously self-propel toward fouled surfaces, driven by the surface-tension gradient (Marangoni stress) induced by the presence of contaminants (Ubal et al. 2021).

(van Wijngaarden 2016). Microbubble collapse also generates local hot spots that facilitate the decomposition and cleaning of organic contaminants (Didenko et al. 1999). For example, results from experiments by Lee et al. (2015) suggested that the ability of microbubbles to remove bovine serum albumin from microfiltration membranes is due in part to pyrolytic decomposition of the proteins attributable to high temperatures produced during bubble collapse.

Another important cleaning mechanism that does not involve cavitation combines two interfacial processes. The first is the ability of the microbubbles to self-propel toward contaminated surfaces; the second is their propensity to attach to fouling materials. When in close proximity to fouling materials, microbubbles can rapidly attach to the contaminants, including hydrophobic ones such as oil, fats, and organic foulants. In a striking illustration of this process, high-speed visualizations by Dudek et al. (2018) demonstrated that an oil droplet can rapidly spread on the surface of a microbubble, forming a thin coating film only a few milliseconds after contact. In addition to this attachment process, microbubbles can spontaneously self-propel toward fouled surfaces (**Figure 5**). The active motion is driven by a phenomenon called the Marangoni effect, which arises when nearby fouling material locally reduces the surface tension in front of a bubble, pulling it forward in the direction of the contaminated surface (Ubal et al. 2021). Combined, these two interfacial phenomena create an efficient cleaning mechanism in which microbubbles self-propel in the surrounding liquid toward the fouled surfaces and rapidly attach to the fouling material before eventually being carried away by the bulk flow. In addition, the fast liquid flow leaving the tiny gap formed between the approaching bubbles and the contaminated surface originates shear and normal stresses that contribute to surface cleaning (**Figure 5*c***).

Decontamination of Food Products

Microbubbles can help remove microorganisms and harmful chemical residues from liquid foods and from the surface of foods such as fruits and vegetables. However, recent research has shown that selecting the right microbubble gas (e.g., ozone, carbon dioxide) or sanitizing adjuvant is critical to achieving effective decontamination with minimal damage to the food substrate.

Ozone microbubbles and, in certain conditions, carbon dioxide microbubbles are promising decontamination agents. Early studies by Ikeura et al. (2011; 2013a,b) demonstrated that ozone microbubbles significantly enhanced the natural capacity of ozone to remove pesticide and fungicide residues from common fruits and vegetables (e.g., lettuce, tomatoes, and strawberries) with little adverse effect on crop quality. More recently, Whangchai et al. (2017) reported that ozone microbubbles effectively neutralized ethion (a resistant organophosphate pesticide) from tangerines with minimal impact on color, acidity, and ascorbic acid content. Ozone microbubble dispersions have also been used to remove phoxim, an insecticide, and chlorothalonil, a nonsystemic fungicide, from vegetable leaves. For example, dispersions with mean bubble size of approximately 40 μm for 15 min were found to remove two to four times more of these pesticides than conventional water baths (Zhang et al. 2021). In addition, a recent comparative study by Li et al. (2021) demonstrated that ozone microbubbles can neutralize residues of pesticides (carbosulfan and trichlorfon) from apples more efficiently than alternative decontamination treatments, such as aqueous ozone, air microbubbles, and hypochlorous acid baths, with minimal effect on fruit color.

Kobayashi et al. (2009, 2012, 2014, 2016) and Kobayashi & Odake (2020, 2022) pioneered the use of carbon dioxide microbubbles as a less expensive alternative to conventional decontamination with high-pressure carbon dioxide. The technique uses dispersions of carbon dioxide microbubbles at comparatively low pressure (~0.5–2 MPa) and near-ambient temperature (30–50°C). The authors showed that the carbon dioxide microbubbles can effectively reduce contamination from microorganisms such as *E. coli*, *Saccharomyces pastorianus*, and *Lactobacillus fructivorans*. For example, treatments at a pressure of 2 MPa and a temperature of 40°C resulted in a 6-log reduction in *E. coli* contamination after 60 min (Kobayashi et al. 2009). Interestingly, both air and nitrogen microbubbles were largely ineffective against *E. coli* contamination under similar treatment conditions. Kobayashi et al. (2022) recently tested dispersions of carbon dioxide microbubbles in combination with electrolyzed water treatments. Their results showed that the removal of diazinon (an organophosphorus insecticide) from broccoli with electrolyzed water is more effective in the presence of the microbubbles, possibly because they enhance the transport of electrolyzed water into the small crevices of the plant.

A revelatory recent study by Singh et al. (2021) tested different combinations of microbubble gas (air, nitrogen, and carbon dioxide) and small concentrations of common antimicrobial agents (chlorine, citric acid, lactic acid, and peracetic acid solutions) against *E. coli* and *L. monocytogenes* contamination. Carbon dioxide microbubbles yielded the strongest antibacterial activity against both *E. coli* (with added chlorine) and *L. monocytogenes* (with added peracetic acid). For example, carbon dioxide microbubble dispersions with added ~200 ppm chlorine resulted in a 5.2-log reduction for *E. coli* compared with a 3.8-log reduction without the microbubbles. Remarkably, air and nitrogen microbubbles did not increase the efficacy of the chemical antimicrobial agents (Singh et al. 2021). This last finding is in qualitative agreement with a recent study by Zhang & Tikekar (2021) in which air microbubble dispersions provided no significant improvement against *E. coli* contamination in blueberries, baby spinach, and grape tomatoes in aqueous solutions of chemical sanitizers.

When generated by power ultrasound, however, air microbubbles have consistently been proven effective at reducing a variety of chemical and microbial contamination in foods; early results are thoroughly discussed in an excellent review by Kentish & Feng (2014). More recently, cavitation microbubbles have been employed to remove pesticides from fresh vegetables (reviewed in Azam et al. 2020), as well as from ready-to-eat salads and fresh-cut fruits (Chen et al. 2020). In combination with other techniques, such as ozonation, ultraviolet light, and mild thermal treatments, microbubble cavitation has also been used to remove contamination from allergens, mycotoxins, and heavy metals (Yuan et al. 2021).

Although some of the efficacy of microbubbles arises from their greater dispersion throughout the liquid and their relatively fast transfer of gases at active sites, their decontamination ability has been often attributed to the generation of highly reactive oxygen species during microbubble shrinking and collapse. For example, microbubble collapse and ozone self-decomposition are thought to enhance the generation of highly reactive hydroxyl radicals (Jothinathan et al. 2021, Liu et al. 2020). However, there have been few formal studies on the actual kinetics mechanisms governing the degradation of contaminants using microbubbles (Liu et al. 2020, Zhang et al. 2021), and further research in this area is vital for accelerating the kinetic-based design of more efficient decontamination treatments. Moreover, apparently bigger questions remain, as new research suggests that the generation of hydroxyl radicals due to microbubble collapse is not as important as previously believed. John et al. (2022) compared the generation of hydroxyl radicals during microbubble ozonation (with a mean bubble size of 37 μm) and conventional bubble ozonation (with a mean bubble size of 5.4 mm). After controlling for factors such as effective ozone dose, they found no evidence that microbubble ozonation generated significantly more hydroxyl radicals than conventional ozonation.

Reduced-Fat Dispersions

Controlling obesity is important to prevent various types of serious diseases, such as diabetes, some cancers, and cardiovascular diseases. Obesity has a variety of causes but is commonly considered the result of an imbalance between energy intake and expenditure. One response from the food industry to the emerging obesity epidemic has been to design healthier ingredients to reduce unnecessary intake of oil and fats.

Several strategies have been proposed for the design of healthier ingredients using microbubbles to partially replace oil in emulsions. One attractive approach is the design of low-fat triphasic dispersions. These are dispersions produced by mixing air microbubbles with an oil-in-water emulsion under high shear. The success of this approach depends on adding a suitable stabilizing shell to the microbubbles to emulate the consistency and creamy mouthfeel of the oil droplets they are designed to replace (**Figure 6**). Progress toward this goal has been made using hydrophobins and other cysteine-rich proteins to provide the stabilizing shell to the microbubbles (Cox et al. 2007; Dimitrova et al. 2016; Tchuenbou-Magaia et al. 2009, 2011). Hydrophobins

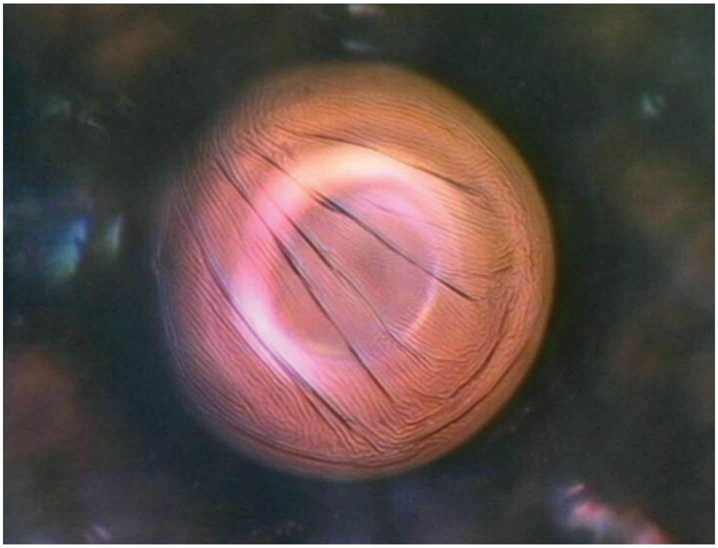

Figure 6

A microbubble stabilized by hydrophobins. Hydrophobins are highly surface-active proteins found in fungi that are able to self-assemble at the interface of microbubbles, forming a viscoelastic stabilizing shell. Figure adapted with permission from Cox et al. (2007).

are surface-active proteins found in fungi that can form strong viscoelastic shells that provide remarkably high bubble strength and longevity (Dokouhaki et al. 2021). Characterization experiments (Tchuenbou-Magaia & Cox 2011) showed that, if well-designed, these low-fat dispersions could exhibit consistency and tribological behavior comparable to those of moderately concentrated oil-in-water emulsions. However, a series of carefully planned sensory studies (Rovers et al. 2016) showed that most panelists could still differentiate the original oil-in-water emulsions from the corresponding triphasic versions containing microbubbles. The perceived difference was attributed to the mouthfeel provided by thin oil films formed on the mouth surfaces due to the coalescence of the oil droplets, a lubrication process that is less pronounced in the reduced-fat systems carrying less oil.

A more recent strategy to design reduced-fat ingredients is to disperse air microbubbles directly in oil, such as vegetable oil. These biphasic dispersions, known as oleofoams, may require unconventional oil-soluble surfactants or particle (Pickering) stabilizers, which possess remarkable stability. Pickering stabilization is provided by crystal particles (e.g., fat and surfactant crystals) that form a tightly packed shell at the bubble interface. Jamming of the crystal particles at the bubble interface hampers coalescence and slows Ostwald ripening, imparting longevity, while crystals in the bulk phase provide network stabilization. These oil–microbubble dispersions offer opportunities for the development of a series of novel food products with reduced oil content and engineered textures (reviewed in Heymans et al. 2017). However, new research shows that manufacturing conditions could strongly affect the stabilizing crystal properties (Fameau & Binks 2021), calling for further studies on the influence of processing on stability and shelf life. Recently, this approach was successfully applied to the preparation of reduced-fat sauces. For example, Saremnejad et al. (2020) replaced up to 80% of the oil in mayonnaise by dispersing air microbubbles in sunflower oil. They found that the color, stability, and consistency of the reduced-fat formulation were comparable to those of the conventional product. Microbubbles have also been used to reduce the calorie density of cocoa butter. Metilli et al. (2021) designed a mix of cocoa butter, sunflower oil, and air microbubbles to create stable dispersions with approximately 30% of the caloric density of the full-fat counterpart. These mixtures were reported to be highly stable to drainage and coalescence with air volume fractions up to 66%, opening up great opportunities for the creation of novel reduced-fat products (Dickinson 2020, Ewens et al. 2021).

Unfortunately, the range of oil-soluble particles suitable for microbubble stabilization that are allowed in foods is quite limited (Kokini & van Aken 2006). A recent study by Qiu et al. (2021) set out to address this shortcoming. These authors proposed an innovative design using medium-long-chain diacylglycerol, a lipid emulsifier with beneficial health properties. Medium-long-chain diacylglycerol crystals combined with β-sitosterol, a plant sterol with anti-inflammatory properties, formed highly stable Pickering microbubbles, potentially paving the way toward the development of a new class of healthy, low-calorie emulsions. However, sensory studies for these designs are lacking, and further research is needed to characterize the sensory properties of these novel ingredients.

Mechanical Effects of Microbubbles in Food

Incorporating microbubbles into the food matrix can provide safe and inexpensive avenues to modify the mechanical and thermal properties of solid and liquid foods. Being able to modify and eventually control these properties is key to process optimization and critical to the design of new and improved food materials.

Wilson and colleagues (Torres et al. 2013, 2015) have shown that adding microbubbles into a viscous liquid food may cause the food to become less viscous and more elastic (i.e., viscoelastic).

For example, an early study (Torres et al. 2013) found that incorporating microbubbles into honey—essentially a Newtonian liquid—significantly decreased its viscosity and induced strong elastic behavior such as large stress relaxation and normal stress differences. In an extension of this study (Torres et al. 2015), the authors showed that incorporating microbubbles into weakly elastic non-Newtonian liquid foods (in this case, dilute guar gum solutions) strongly enhanced their preexisting viscoelasticity. Importantly, by aligning these experimental observations with existing theories, these researchers identified the mechanism responsible for the observed behavior. They found that the changes in the flow properties agreed well with a rheological model developed by Llewellin & Manga (2005) as an extension of the well-established Jeffreys model. This agreement suggests that the enhanced viscoelastic behavior can be understood in terms of the microbubbles aligning and stretching with the flow. Stretched by fluid stresses, the microbubbles act like elastic springs, providing increased resistance to deformation as they stretch and incorporating these elastic forces into the viscous liquid.

Microbubbles have also been introduced into liquid foods to improve the mechanical properties of their solid phase. In a recent study by Babu & Amamcharla (2022), microbubbles were added to liquid milk protein concentrate to facilitate spray drying and improve the functional properties of the resulting dried product. Specifically, liquid milk protein concentrate was passed through a Venturi microbubble generator to produce a fine bubble dispersion as a pretreatment before spray drying. The result of the pretreatment was twofold. The viscosity of the concentrate decreased by approximately 65%, which could enable spraying of more concentrated solutions, and the microstructure of the dried protein clusters loosened, resulting in better rehydration properties of the dry powder.

Constitutive equations relating stress to deformation that are able to explain and predict the mechanical effect of the microbubbles in solid foods are not generally known, but a recent university–industry collaboration may provide new insights into the role of microbubbles in the stress–strain response of solid-food matrices (Bikos et al. 2021, 2022a). Results so far have shown that nitrogen microbubble dispersions (with bubbles approximately 20–60 μm in size) incorporated into melted chocolate resulted in a significant decrease in Young's modulus and the threshold fracture stress and strain of the solidified material, both of which enhance the brittleness of the solid chocolate. This behavior, the researchers found, is well-described by a nonlinear viscoelastic constitutive model developed by Kichenin et al. (1996) for plastic materials (e.g., polyethylene). The model suggests that the mechanical effect of microbubbles in a solid-food matrix could be mediated by two dissipative mechanisms: a viscoelastic (Maxwell) deformation and an elasto-plastic strain acting in parallel. In addition, an analysis of the resulting microstructure suggested that microbubbles could create stress concentration spots in the solid matrix, reducing the threshold strain for the initiation of propagating cracks.

The air inside the microbubbles conducts heat poorly, and because the small bubbles are separated from one another, the trapped air cannot easily transport heat through convection. Recently, Bikos et al. (2022b) demonstrated that incorporating microbubbles into the food matrix can provide an effective and inexpensive way to modulate the thermal properties of solid foods. For example, they found that incorporating ~15% air microbubbles by volume decreased the thermal conductivity of solid chocolate by ~20% while increasing its specific heat capacity by ~10%. The authors used these observations to develop and validate a multiphase heat-transfer model. The availability of these mechanistic models is important for solving processing problems and developing new products, for example, to predict the optimum number density and spatial distribution of microbubbles needed to provide the desired thermal response during processing, preparation, or consumption of solid foods.

Food Production

The global food system is expected to feed a population that will increase to nearly 10 billion by 2050. Yet some of the toughest food security and sustainability challenges facing the food system, like land and water scarcity, are becoming worse. Hydroponic and vertical farms could help ease these challenges by growing food plants in nutrient-rich solutions instead of soil. By recirculating the water and nutrients that are not taken up by the plants, such farms would also use substantially less water than conventional farming, improving their sustainability and making it easier to grow crops in arid climates. However, low levels of dissolved oxygen in the nutrient solution could hinder plant growth and make the plants more susceptible to diseases.

Aeration using microbubbles is an efficient way to maintain high levels of dissolved oxygen because of their large collective surface area and rapid dissolution rates. Accordingly, microbubble aeration has been found to enhance the growth, mineral content, and chlorophyll content of fresh produce cultivated hydroponically, including spinach, komatsuna, field mustard, and romaine and iceberg lettuce (Abu-Shahba et al. 2021, Ebina et al. 2013, Ikeura et al. 2017b, Park & Kurata 2009). These benefits, however, are highly dependent on a variety of factors: Microbubble properties such as size and number density, biological factors such as plant species and growth phase, and environmental factors such as pH and nutrient concentration all play an important role in modulating the effect of the microbubbles and have to be carefully considered (Iijima et al. 2020, Tsuchida et al. 2021).

For example, the benefits of microbubble aeration on plant growth strongly depend on sufficiently high bubble number density. However, methods that produce a high density of microbubbles (e.g., pressurization systems) are also thought to increase the concentration of hydroxyl radicals generated during microbubble collapse. Moreover, at high concentrations, these hydroxyl radicals have phytotoxic effects that can cause poor plant growth (Ikeura et al. 2017a), and a high density of microbubbles can induce osmotic stress in the plant roots. Microbubbles tend to adsorb charged inorganic nutrients and attach to root surfaces, facilitating the uptake of nutrients. However, if the concentration of microbubbles around the roots is excessive, the nutrient solution becomes locally hypertonic, resulting in detrimental osmotic stresses (Ikeura et al. 2018).

Aquatic farms might also help ease the burden on the global food system by growing aquatic organisms under controlled conditions. In the aquaculture industry, aeration of fish farms and ponds using air microbubbles helps maintain consistently high levels of dissolved oxygen crucial for animal health and growth (Tsuge 2014). Because of their low buoyancy, microbubbles can also maintain the desired oxygen levels at high water depths (Endo et al. 2008). The weight of sweet fish and rainbow trout and the growth rate of striped catfish larvae have been reported to increase significantly due to higher dissolved oxygen levels when cultivation ponds are aerated using fine bubbles (Ebina et al. 2013, Subhan et al. 2020). Similarly, microbubble aeration has been used to promote the growth of *Penaeus vannamei*, a common shrimp variety. Recent studies using microbubble aeration reported gains of up to 20% in body length and up to 50% in weight for these shrimp (Lim et al. 2021, Rahmawati et al. 2021). In addition to promoting animal growth, new techniques using fine bubbles could improve fish health in the aquaculture industry. For example, a recent study found that loaches (*Misgurnus anguillicaudatus*) immunized using bath immersion vaccination had a survival rate similar to that of fish vaccinated using the more labor-intensive technique of direct injection when microbubbles were added to the immersion bath (Yun et al. 2019).

Researchers also hope to exploit the aeration ability of microbubbles in cellular agriculture—a nascent method of producing food directly from cells rather than from whole organisms (Rischer et al. 2020). In conventional bioreactors for cellular agriculture, hydrodynamic mixing is commonly used to increase oxygen transfer to the cells by dispersing millimetric bubbles injected into the reactor (Karimi et al. 2013). Strong mixing, however, causes high shear stresses, which damage the cells and curb productivity (Chisti 2001, Ismadi et al. 2014, Merchuk & Gluz 2002, Z. Wang et al. 2020). Enhancing aeration by direct injection of microbubble dispersions is expected to help reduce or eliminate the damaging mixing shear during production. Promising results have been reported for production of yeast and microalgae, and efforts to make the process available for production of cultured meat are underway (Hanotu et al. 2016, Ju et al. 2019, Li et al. 2020).

CONCLUSION

Microbubble technology is inherently a clean technology, a crucial incentive for its adoption by the food industry. As discussed throughout this review, research encompassing microbubble technology has been increasingly successful in designing better food products and improving food manufacturing. But part of this research remains predominantly descriptive and perhaps has focused too little on unifying governing principles.

The challenge, therefore, is to strike an appropriate balance between generating useful data on the effect of microbubbles in food systems and elucidating the physicochemical events that mediate these effects. Doing so would provide vital information for more rapid transformational change to address the wide range of opportunities for microbubble technology. Ultimately, the goal for food scientists will be to integrate fundamental microbubble physics with all the complications related to real food systems.

FUTURE ISSUES

1. Innovations in the equipment and techniques to generate microbubbles will make bubble generation in food production systems cheaper and more convenient.
2. Improved understanding of the generation of high temperatures and radical species near collapsing microbubbles will assist in their application as disinfecting and cleaning agents.
3. Development of physical understanding for the interaction and potential collapse of microbubbles in more complex media will provide new avenues for innovation in food materials.
4. Contributions of microbubbles to the rheology of food materials are only beginning to be understood and could provide an effective mechanism to alter the viscoelasticity and sensorial attributes of food products.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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