

Formulation, characterization, and applications of nanobubbles in food processing: A review

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ABSTRACT

The evolving field of food processing is witnessing the rise of the versatile, multifaceted domain of nanobubble technology, with potential applications spanning food preservation. Nanobubbles, owing to their extremely small size, enhanced surface area, increased mass transfer rates, greater stability, and higher dissolution rates, are highly valued technologies that warrant further exploration to capture their unique benefits. This review highlights the importance of nanobubbles in the field of food processing. It outlines methods for generating nanobubbles, including physical and chemical approaches, with due consideration of the critical elements for their synthesis and characterization. It has significantly underscored the importance of bubble size and stability with key considerations of zeta potential and mass transfer kinetics. Further, the review highlights the methods and scope for employing nanobubbles in food processing and allied sectors. The key understanding of nanobubble formation and its process optimization for improved efficiency is presented. Further, the review presents a roadmap for improved stability and the delivery of anticipated benefits of nanobubble technology by establishing synergy among consumer requirements, operational efficiency, and regulatory requirements.

1. Introduction

The phenomenon of bubble formation is governed by the interaction between the vapor pressure and the surrounding pressure in a liquid. Bubbles are formed when the pressure in a specific area decreases below the vapor pressure (Gupta et al., 2016). This can occur due to heating (boiling), reduced pressure, or dynamic pressure changes (cavitation). As the pressure within a liquid decreases below its vapor pressure, the liquid's molecules have sufficient kinetic energy to overcome intermolecular forces and form vapor bubbles. Thus, cavitation can be defined as a fluid phenomenon characterized by the formation, expansion, and explosion of gas-filled bubbles within a liquid due to localized decreases in pressure below the vapor pressure (Sharifishourabi et al., 2024). The rapid disintegration of these bubbles produces shockwaves and

high-velocity microjets, potentially damaging materials and reducing hydraulic system efficiency. Nanobubbles, characterized by their small size and surface effects, are gas-filled bubbles with sizes usually in the range of 10–1000 nm. Unlike larger bubbles, they have unique characteristics and manufacturing methods. When the quantity of gas dissolved in a liquid exceeds its solubility limit, a solution with an elevated concentration is formed, leading to the formation of nanobubbles (Zhou et al., 2021). Rapid changes in temperature, pressure, or chemical reactions can result in supersaturation. The early formation of gas pockets is facilitated by nucleation sites, which include pollutants or uneven surfaces.

Acoustic cavitation is a complex process that involves the interaction of an acoustic field with pre-existing nanobubbles or gas nuclei in the liquid medium. It displays multiple forms, which are primarily

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categorized as nucleation, stable cavitation, and inertial cavitation. Nucleation is the formation of new bubbles, mainly due to variations in localized pressure, typically with an increase in acoustic pressure amplitude exceeding the tensile strength of the liquid. Stable cavitation occurs when bubbles undergo periodic oscillations around an equilibrium size under the influence of an acoustic field, without violently collapsing. In contrast, inertial or transient cavitation is characterized by the unstable and rapid growth of bubbles followed by their violent collapse, which generates extreme localized conditions, including elevation in temperatures (~ 5000 K) and pressures (>1000 atm), along with shock waves and microjets, which lead to enhanced mass and energy transfer (Mondal et al., 2021).

Various parameters, such as ultrasonic frequency, intensity, and the physicochemical properties of the medium, greatly enhance the dynamics of acoustic cavitation. At lower frequencies (<100 kHz), inertial cavitation is more prevalent due to a higher likelihood of bubble collapse. In contrast, at higher frequencies (>1 MHz), stable cavitation becomes more pronounced, contributing to increased shear forces and enhanced diffusion (Mondal et al., 2021). Thus, understanding all cavitation regimes is crucial for optimizing their applications across sectors such as food processing, bioactive compound extraction, and emulsification, where precise control over bubble behavior is necessary to achieve desired physicochemical modifications without inducing degradation.

Further, Brownian motion affects ultrafine bubbles, often called nanobubbles, due to their low buoyancy. As a result, their slow ascent rates enable them to stay underwater for prolonged periods. Regarding remarkable properties such as increased energy and the release of free radicals upon collapse, nanobubbles are superior to microbubbles in terms of surface area per unit volume. The concentration of nanobubbles was significantly reduced when the ultrasonic frequency was raised from 22 kHz to 1 MHz. The concentration of nanobubbles showed an increasing trend with increasing ultrasonication power and duration, gradually falling or reaching a steady state with longer sonication times.

Gaseous areas with a radius ranging from tens to hundreds of nanometres, greater than what is visible to the unaided eye or may be observed by traditional microscopic techniques, are known as nanobubbles (NBs). Examination through Atomic Force Microscope (AFM) imagery has revealed their spherical cap morphology, yet the exact configuration of these NBs remains undefined. Following the initial postulation of nanobubbles (NBs), research into their properties has evolved rapidly. Despite ongoing efforts to fully explain the observed formation of stable NBs in water, a multitude of NB applications have emerged across multiple disciplines (Malahlela et al., 2024). This includes sectors where NBs can potentially replace or enhance the effectiveness of treatments currently used in water and wastewater purification. Nanobubbles (NBs) represent enduringly stable spherical enclaves of gas immersed within a liquid medium. For practical reasons, they are described as having dimensions smaller than 1000 nm, often lining up with about 100 nm in one dimension. Interestingly, NBs with diameters less than 13 nm collapse rapidly, disappearing within a minute. Nanobubbles (NBs) are characterized by a number of intriguing and unique properties, including a high surface area relative to volume, outstanding stability, and extraordinary endurance. This leads to important applications in the fields of environmental and mining-metallurgy. Moreover, NBs can be employed to study interfacial phenomena, including adsorption kinetics on hydrophobic surfaces, microfluidics, and long-range hydrophobic attraction.

Nevertheless, data remain scarce on the efficient preparation of concentrated water dispersions containing NBs and on a comprehensive understanding of their physicochemical and interfacial properties. Nanobubbles manifest as remarkably enduring adsorbed entities that can be observed at interfaces or surfaces as interfacial NBs. Subsequently, they disperse and form pancake-like structures or transform into liquid dispersions, commonly referred to as bulk NBs. Nanobubbles (NBs) are gaseous regions that generally range from tens to hundreds of

nanometers in radius, dimensions below the threshold of visibility for the unaided eye and conventional microscopes. Observations made using the Atomic Force Microscope (AFM) have unveiled their tendency to adopt spherical cap forms. Yet, the exact configuration of these NBs remains unclear. The prevailing belief is that bulk nanobubbles (NBs) are enduring cavities that hold gas content, influenced by unpredictable Brownian motion. Current understanding suggests that these bulk NBs exist in water under room temperature conditions due to the initiation of steadfast bubble formation. This implies the presence of a nanoscale water-affinity attribute, in which the lack of structure in a liquid becomes unsettled, prompting an automatic reduction in local density and the emergence of minuscule empty spaces. These empty spaces can function as centers for bubble formation, which are subsequently upheld by ions, often referred to as "bubstones". Interest in nanobubbles has surged in the past decade, driven by numerous industries recognizing their diverse potential applications across sectors. Nanobubbles (NBs) are primarily used in wastewater treatment and purification, mining, agriculture, agro-food processing, aquaculture, and medical applications (Yaparante et al., 2024). Depending on their size and chemical composition, nanobubbles (NBs) may operate according to different principles in the food processing industry. For instance, gaseous NBs are known to influence the rheological properties of food by reducing interparticle friction among colloidal particles, thereby modifying the liquid's physical characteristics. Certain concentrated dairy combinations, such as dispersions containing whey and milk proteins, have been reported to become less viscous when carbon dioxide-based NBs are added.

An alternative impact of gaseous nanobubbles (NBs) on food and bioprocessing could be to improve the solubility profile of gases and enhance mass transfer efficiency. Given the extensive range of potential applications for nanobubbles (NBs), there is a prevailing expectation that NBs could emerge as a significant catalyst for advancing processing technologies in the food industry. In reality, gas-filled bubbles have proven instrumental in influencing beverages' stability, microstructure, and functional attributes. Extensive research has examined the behavior of foams and the properties of gas phases in relation to food quality. This exploration has solidified the link between the process, the end product, and its functional aspects. Consequently, the intriguing aspect lies in the potential use of nanobubbles (NBs), especially in the production of foam-based products, foods enhanced with gel and cream, fizzy drinks, and dietary supplement carriers. Within these contexts, the presence of NBs offers the promise of greater stability, more even gas distribution, innovative textures, and enhanced functionality. In contrast, it appears feasible to leverage NBs' benefits to sanitize work surfaces, thereby boosting the effectiveness of food manufacturing procedures. The food industry benefits from incorporating nanobubbles (NBs) to develop novel food products, thereby providing a better understanding of the mechanism of nanobubbles in the food matrix. Based on this, the objective of the review was to discuss nanobubble generation techniques, physicochemical properties, and factors that impact nanobubble formation. This review discusses various mechanical methods for generating nanobubbles, including hydrodynamic cavitation, acoustic cavitation, optical cavitation, particle cavitation, surface electrostatic nanobubble development, and ultrasonic treatment. A comprehensive discussion was held on different chemical techniques, including electrolysis, plasma, and surface nanobubbles. This paper examines several parameters that influence the creation of nanobubbles, including temperature, pressure, gas composition and concentration, surfactants, electrolytes, pH, and the presence of mono and multivalent salts. An analysis is conducted of the uses of nanobubble technology across many areas, including nanobubble-assisted freezing, crystallization, protein foam fractionation, and films/gels.

2. Physico-chemical properties

While the characterization of nanobubbles (NBs) remains an

evolving concept, with ongoing discussions and no unanimous agreement, these structures are generally regarded as minuscule gaseous voids with dimensions ranging from 1 to 1000 nm. The remarkable properties of nanobubbles (NBs) in aqueous solutions include increased solubility, increased zeta potential, free radical production, exceptional coalescence resistance, considerable surface area, and the release of substantial energy upon bubble dissolution.

2.1. Bubble size, size distribution, and rising velocity

The formation of a macro bubble, micro bubble, and nanobubble is presented in Fig. 1. Cavitation bubbles have been categorized based on their dimensions, distinguishing between macrobubbles (MaBs) (larger than 100 μm) being visible to the naked eye, microbubbles (MBs) (0.5–10 μm in diameter), or larger bubbles (measuring 1–10 mm), fine bubbles (ranging from 10 to 15 μm), and ultra-bubbles (with sizes smaller than 200 nm) and nanobubbles (less than 1 micrometre) (Zhao et al., 2023). The range of sizes in which macroscopic non-spherical microbubbles (MNBs) form due to the depressurization of water saturated with air is influenced by multiple factors. Water saturation pressure is the main factor, whereas temperature and air saturation level are the only secondary factors in this size distribution. The formation of MNBs (microbubbles that are not perfectly spherical) during the depressurization of water saturated with air is influenced by several factors. The dominant factor is the water saturation pressure, with air saturation level and temperature having a comparatively minor influence on the size distribution. Furthermore, the attributes of the phase contact duration depend on the bubble's ascent speed. This, in turn, affects the transfer of substances across interfaces and the mixing of pollutants. Analyzing the distribution patterns of bubble size and velocity can be crucial for improving the design and operational parameters of bioreactors, as these parameters are important for understanding hydrodynamics and process efficiency (Albanese et al., 2019).

Various analytical approaches can be employed to characterize the bubble size, bubble size distribution, and other properties. These approaches include (a) Dynamic Light Scattering (DLS), which is used to determine the size distribution of nanobubbles in suspension. (b) Nanoparticle Tracking Analysis (NTA): Provides real-time visualization and size distribution analysis of individual bubbles. (c) Cryo-

Transmission Electron Microscopy (Cryo-TEM): Enables direct imaging of nanobubbles at nanometer resolution. (d) Atomic Force Microscopy (AFM): Used to analyze the morphology and mechanical properties of nanobubbles at the solid-liquid interface. (e) Laser Scattering and Shadowgraphy Methods: Applied for measuring bubble size in dynamic systems. (f) X-ray Computed Tomography (X-ray CT): A non-destructive technique to visualize bubble distribution in various media.

While numerous analytical approaches are reported for the assessment of nanobubble (NB) properties, their comparative evaluation can provide a more comprehensive understanding of data reliability. Dynamic Light Scattering (DLS) is one of the most frequently used techniques for evaluating the size distribution in suspension; however, its averaging may not clearly reveal the presence of multiple bubble populations, particularly those below 50 nm. Nanoparticle Tracking Analysis (NTA) seeks to overcome this gap by monitoring individual bubble trajectories, thereby providing real-time size data along with concentration data; however, the optical scattering mechanism limits its resolution for very small NBs. Cryogenic Transmission Electron Microscopy (cryo-TEM) allows direct nanoscale imaging, but this technique requires freezing and vacuum conditions to modify the bubble morphology. Further, Atomic Force Microscopy (AFM), which is widely used for surface NBs, provides detailed topography, including adhesion mapping, yet the interaction of the probe may deform the delicate bubbles. Also, the X-ray Computed Tomography (X-ray CT) and Laser Shadowgraphy techniques greatly extend the analysis to opaque and complex matrices, thus enabling the three-dimensional visualization of NB distribution without disrupting the sample (Xu et al., 2025).

Recent studies have also recommended combining optical and microscopic methods to enhance measurement accuracy and capture NB stability over time. For instance, Malleshham et al. (2025) demonstrated that the correlation of NTA with cryo-TEM yields better insight into the heterogeneity of NB and persistence, while this study also highlighted how the complementary use of AFM and DLS can distinguish between bulk and surface NBs in mixed systems. Collectively, these techniques provide a very coherent framework for assessing the size, morphology, and electrokinetic stability, thus allowing a more consistent interpretation of nanobubble behavior in aqueous environments. The analytical techniques used to characterise the bubble size and distribution include Stokes' law and other empirical or semi-empirical relationships based on

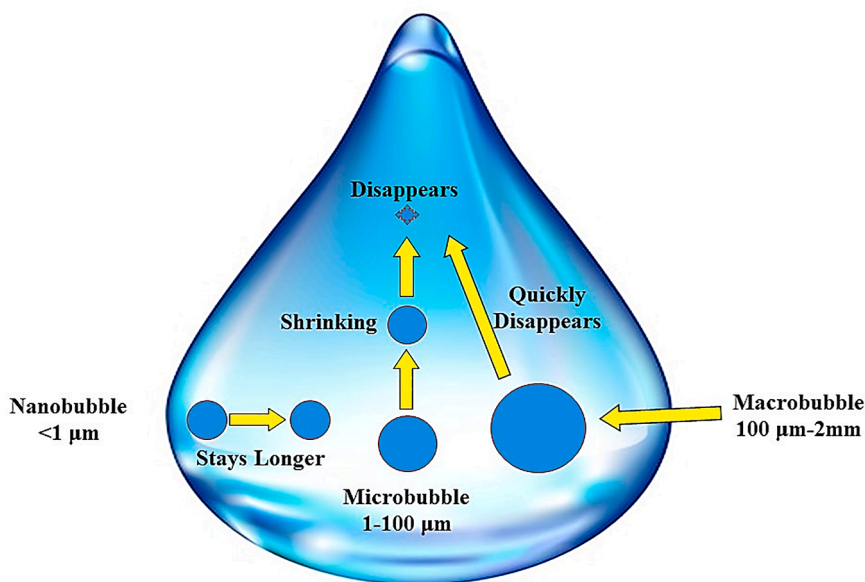


Fig. 1. Formation of macro bubble, micro bubble and nanobubble.

fluid dynamics, laser-based methods, X-ray attenuation, electrical resistivity measurements, and image analysis. The form of bubbles and their ascent speed can also be deduced using principles of fluid mechanics, as depicted in Eq. (1). The Velocity at which the bubble rises hinges on its form. In instances where bubbles are small, the inertial force is notably lower than both surface tension and viscous force, leading to their spherical configuration.

$$v_b = g \rho_L d_e^2 / (18 \mu_L) \quad (1)$$

In this context, the bubble's upward velocity (v_b) is a function of various factors: gravitational acceleration (g), liquid medium density (ρ_L), the bubble's volume-equivalent diameter (d_e), and the liquid medium viscosity (μ_L). Additionally, the average diameter (D_b) of macro-bubbles (MBs) can be determined using a fluid-dynamics correlation based on Stokes' law. This correlation accounts for the influence of bubble concentration on the liquid volume fraction (ϵ_L), particularly in the low-Reynolds-number Stokes regime (< 0.2). This relationship is represented by in the following equation.

$$D_b = \left[\frac{18 \mu_L v}{(\rho_L - \rho_G) * g * \epsilon_L^{4.65}} \right]^{0.5} \quad (2)$$

Here, v is the superficial velocity or terminal velocity of the bubble front within the liquid medium measured in m.s^{-1} , ρ_G signifies the density of the gas phase. The dispersion coefficient (δ) for bubble sizes is used to evaluate bubble size uniformity, as outlined in the following equation.

$$\delta = (D_b^{90} - D_b^{10}) / D_b^{50} \quad (3)$$

In this context, D_b^{90} , D_b^{50} , and D_b^{10} denote diameters corresponding to 90%, 50%, and 10% of the volume, respectively. The value D_b^{50} refers to the average bubble diameter on the cumulative distribution curve of relative bubble sizes (Albanese et al., 2019). Macro bubbles (MBs) have a noticeably slow ascension pace, which has been demonstrated by studies that describe the relationship between bubble diameter and ascending velocity, i.e., the larger the bubble, the larger the buoyant force and, therefore, the higher the ascension rate, which is related exponentially to the inverse of bubble diameter. Another method to

describe and determine bubble size is to study the pattern of the relationship between dissolved oxygen (DO) content and bubble dimension. This study found a negative correlation between bubble size and steady-state dissolved oxygen content (Albanese et al., 2019).

The state of equilibrium for dissolved oxygen (DO) concentration is the point at which the gradual rise ceases, indicating an increase in the number of generated bubbles. DO in water is measured with a DO sensor. Determining bubble size involves deriving an average value from the particle counting method (PCM) across various pressure conditions. The fluorescence quenching technique is used to determine the concentration of oxygen near the meter's sensor. While it may seem simple to compare bubble sizes produced under various conditions using the reverse estimation of dissolved oxygen (DO) method, its practical application necessitates a larger dataset for the empirical model and additional research to achieve higher accuracy in bubble size estimation. Alternatively, probability distribution functions and cumulative distribution functions can be used to improve precision with a small dataset. Although they live alongside NBs, reactive oxygen species (ROS), including hydroxyl radicals, superoxide radicals, and singlet oxygen, are not readily measurable. Instead, their interaction with probe molecules is used to determine their amounts. Adding chemicals such as H_2O_2 and copper, or exposing the system to UV radiation, can accelerate ROS formation. Despite being influenced by external forces such as buoyancy and gravity, nanobubbles also exhibit Brownian motion, which is independent of these forces. Fig. (2) illustrates the formation of nanobubbles by continuously passing air and water through the generator and analyzing the results under various circumstances.

2.2. Persistence and stability

The time NBs remain in the solution is a measure of their endurance. This stability is beneficial because it increases the time the gas spends undergoing a mass transfer reaction with water molecules, which can last from an hour to several months. Their low upward velocity enhances the stability of bubbles due to Brownian motion. This stability is particularly pronounced in smaller, stable NBs, which exhibit elevated zeta potentials. By maintaining higher pH values along with a significant concentration of OH^- ions, these NBs can be generated (Ahmad et al.,

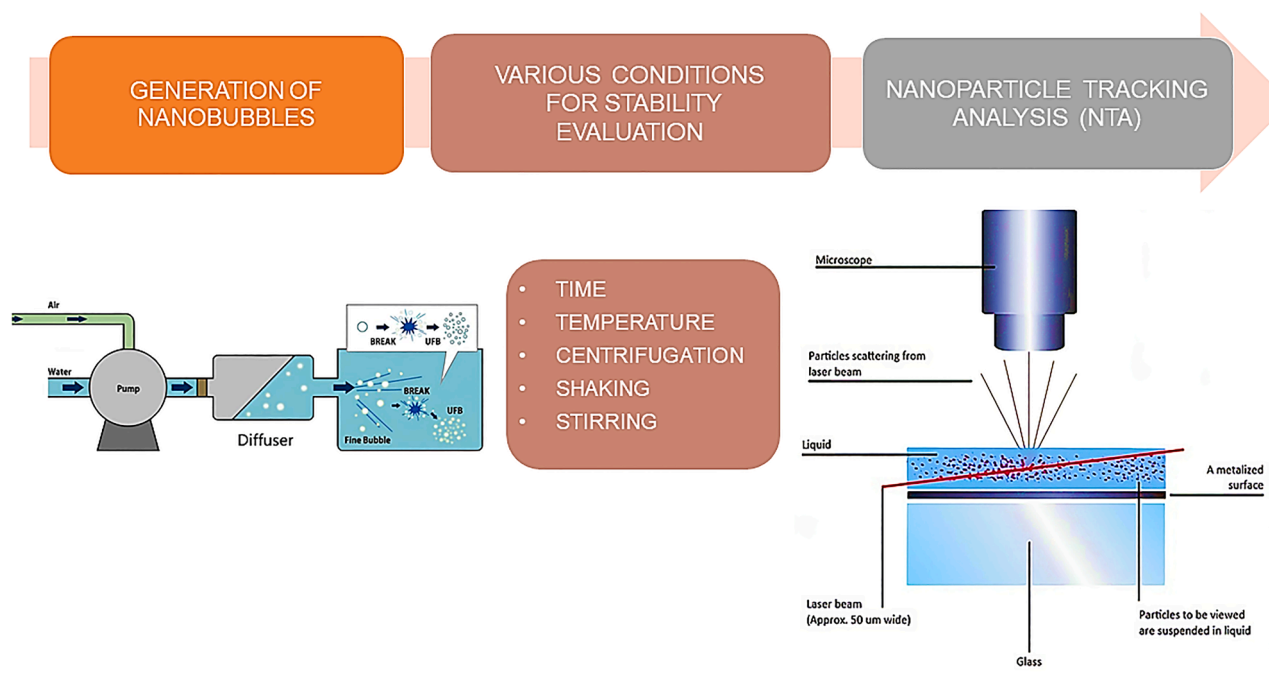


Fig. 2. Diagrammatic representation of NB generation and analysis of their stability after exposure to different conditions.

2018). Additionally, at the boundary between the gas and water phases of the bubble, OH^- ions or less hydrated and more polarised anions are related to the surface charge of NBs. Moreover, at elevated pH levels, NBs exhibit increased resilience against becoming trapped within porous media. This heightened stability is predominantly linked to the diffusional characteristics of the bubble interface.

The durability of large quantities of NBs warrants more comprehensive exploration. Regarding their long-term stability, certain factors come into play, such as the buoyant force, which is of minor consequence, impeding bulk NBs from ascending to the open surface; instead, their motion is dominated by Brownian motion and their resistance to dissolution. Experimental observation reveals that NBs can be tracked to confirm their stability. In particular, the introduced organic material adheres to the surface of NBs, thereby enhancing their stability. Images were taken using a MEMS chip during transmission electron microscopy to verify this without the requirement for freezing. In order to prevent the coalescence of formed bubbles and improve stability, there must be a repulsive force created by the electrically charged interface between liquid and gas molecules. The low concentration gradient between the interface and the surrounding liquid, maintained by the high dissolved gas concentration in the water, enhances this action. NBs possess a surface that is both impermeable and kinetically steadfast, rendering them more resilient against diffusion. Nevertheless, elevated gas flow rates accompanied by higher bubble concentrations can increase the risk of bubble coalescence, leading to larger, more unstable macrobubbles. This holds despite elevated zeta potential values. Therefore, bubble density should be considered to prevent bubble coalescence. The ability of NBs to retain stability in liquids under normal conditions has been a matter of discussion for a considerable time and is consistent with well-accepted thermodynamic theory.

Henry's law predicts that NBs' internal pressure will be significantly higher than the outward pressure of the surrounding solution. This difference causes the bubble to collapse and dissipate abruptly in an instant of microseconds. Due to their dimensions, the stability and existence of NBs might appear implausible. However, numerous investigations have revealed that NBs can indeed exhibit remarkable longevity within liquid solutions, with observable lifespans spanning hours, days, weeks, or even months under specific favourable conditions. A theoretical viewpoint suggests that incorporating anions into the interface of NBs may affect their durability. Electrostatic repulsive forces might be generated by ions adhering to the nanoscale interface of NBs, thereby balancing the external restraining pressure. Either persistent stability in NB diameter or the segregation of air particles within NBs from the surrounding liquid could arise from the equilibrium between these opposing forces. Additionally, because of their smaller micro-scale diameters, NBs have larger specific surface areas than macro bubbles with the same volume. This property increases the efficiency of mass transport and significantly increases the solubility of gases.

The potential existence and enduring stability of NBs in liquid media under standard atmospheric conditions have been a topic of debate for a long time, primarily due to conflicts with classical thermodynamic theories. Following the principles of classical thermodynamic calculations based on the Young-Laplace equation, the pressure within gas-filled cavities, relative to the diameter of the bubbles, can be defined by the following equation.

$$P_{in} = P_{out} + \frac{2\gamma}{r} \quad (4)$$

Herein, P_{in} denotes the internal pressure within a gas-filled bubble; P_{out} represents the pressure of the surrounding liquid; γ signifies the surface tension of the liquid; and r stands for the radius of the bubble.

The internal pressure within the nanoscale bubble would be significantly greater than the external pressure experienced by the surrounding bulk solution. This disparity in pressure conditions promotes the swift dissolution and escape of the bubble within microseconds, aligning with Henry's law. The proposition has emerged that the stability

of NBs may depend on the selective adsorption of anions at their interface. At the nanoscale, ions adhering to the NB interface might trigger electrostatic repulsion, effectively counteracting the constraining force from surface tension. This equilibrium of forces will prevent contact between gas molecules within NBs and the surrounding liquid bulk, and will sustain NB diameter for a significantly extended duration. These events not only prevent NBs from gathering and merging, but they also weaken the internal pressure in each bubble by nullifying the effects of surface tension.

The stability of NBs is closely linked to the formation of a hydrogen bonding network at the gas-water interface, akin to the arrangements observed in ice and gas hydrates. Consequently, this network contributes to the limitation of gas diffusion across the interfacial film. The surface of an NB remains kinetically stable even under substantial internal pressure, and the interface between the gas and water offers significant resistance to diffusion. This phenomenon can be partially explained by Henry's law (Eq. 5), which relates the amount of dissolved gas to the partial pressure of the surrounding gas.

$$C_g = k \times P_g \quad (5)$$

Here, C_g signifies the gas concentration in the aqueous phase; k denotes the specific constant associated with Henry's law, which varies for different gases; and P_g represents the partial pressure of the gas.

As depicted in Eq. (5), the amount of dissolved gas increases as pressure increases. Consequently, the gas enclosed within NBs will take longer to diffuse entirely into the surrounding medium. This indicates that the Laplace pressure and the gas content within an NB experience concurrent increases due to the rising surface tension. As a result, these effects balance each other out, compensating for the driving force of bubble diffusion: surface tension. Additionally, NBs have a significantly higher specific surface area than macro bubbles of the same volume due to their smaller diameter. Increased mass transfer efficiency caused by this characteristic greatly improves gas solubility.

2.3. Gas-liquid mass transfer

The effectiveness of gas-liquid mass transfer can be enhanced by using MNBs. This is justified by the fact that the rate of gas mass transfer depends on the interfacial area between the liquid and gas phases, which is notably greater for MNBs. As a result, the gas-dissolving rate in the water may reach supersaturation levels at this elevated location. It is possible to accelerate the mass transfer rate of MNBs into the surrounding liquid by decreasing the bubble's radius while concurrently raising its internal pressure. Furthermore, the rate of gas diffusion is directly proportional to the pressure gradient. The use of smaller bubble sizes can thereby increase the efficiency of gas transport.

In aerobic biodegradation, dissolved oxygen DO acts as a terminal electron acceptor in microorganisms. Consequently, the aeration efficiency might be constrained by the oxygen transfer rate from gas to liquid and the further uptake rate of microorganisms. This suggests that using smaller bubble sizes, such as MNBs, could enhance gas transfer efficiency, thereby amplifying beneficial reactions in water treatment processes. The rate at which mass is exchanged between two phases can be determined by considering (i) the mass transfer coefficient for liquid-gas interactions, (ii) the concentration difference across these phases, and (iii) the surface area-to-volume ratio. The rate of mass transfer between the gas and the liquid is evaluated using the unsteady-state method. A dynamic approach is employed to determine the mass transfer coefficient for MNBs mathematically. This approach accounts for various factors, including reductions in bubble size and the rate of carbon dioxide transfer as a function of bubble size. The oxygen content within oxygen MNBs surpasses that found in air MNBs and is notably greater than that contained in air macrobubbles. This distinction in gas concentration within the liquid adheres to Henry's law, which establishes a direct correlation between gas partial pressure and its concentration in the liquid. The type of gas present primarily determines the

dissolved oxygen (DO) zenith value. The outcome is that compared to air MNBs, oxygen macrobubbles reach a larger DO peak. The transfer of oxygen, however, proceeds more quickly due to the smaller bubble size.

2.3.1. Distinct mass-transfer behavior of nanobubbles

Although MBs are broadly recognized for enhancing gas dissolution through an increased interfacial area, NBs display fundamentally different mechanisms of gas-liquid mass transfer. The ultrafine diameter (<200 nm), elevated internal pressure, and extremely high surface-to-volume ratio enable them to remain suspended for prolonged periods, primarily due to Brownian motion and electrostatic stabilization (Sharma et al., 2025). The extended residence time increases the effective interfacial area and promotes the continuous gas diffusion, even under dormant conditions. In addition to the collapse of nanobubbles, which generates localized hotspots and reactive oxygen species (ROS) that renew the gas-liquid interface, enhancing transfer efficiency beyond purely diffusion-driven processes (Arias-Torres et al., 2025). A comparative analysis reveals that the NB-based aeration system can improve the overall volumetric mass transfer coefficient (k_{La}) by nearly threefold while requiring a significantly lower energy input than conventional microbubble systems (Li et al., 2025). The extended gas retention and self-pressurizing dynamics of NB also maintain a higher level of dissolved oxygen (DO) for a longer period of time, which is specifically advantageous in applications such as fermentation, food preservation, and wastewater aeration. These findings clearly indicate that the NB-induced enhancement of gas-liquid mass transfer is not simply a scaled-down effect of MBs but arises from distinct physico-chemical and interfacial phenomena that redefine conventional mass transfer kinetics.

2.4. Zeta potential

The descending plane separates the two layers of counterions: one formed ahead of the bubble interface and the other in the bulk solution. It is thought that this plane represents a physical characteristic of suspended NBs. By examining the electrical perspectives or interactions between bubbles and other droplets or entities, zeta potential (ZP) can be used to predict the stability of nanobulks (NBs) in an aqueous solution. Each bubble or particle present within a suspension framework exhibits a consistent Zeta potential (ZP) characterized by a notably high absolute value. Compared with NBs with absolute Zeta potential (ZP) values below 30 mV, the former exhibited considerably higher stability. Studies show that counterionic surfactants promote the creation of negatively charged (−) bubbles, while positively charged ion surfactants can result in the formation of cationic-charged bubbles.

At the interface boundary, also known as the sliding plane, which divides the dual layer composed of counter ions at the bubble interphase and within the bulk solution, the Zeta potential (ZP) of NBs within a suspension is recognized as a physical characteristic. ZP is a valuable indicator of nanobubble (NB) stability in aqueous solutions with charged (−) bubbles, as it provides information on the electric potential difference between the bubbles and the surrounding droplets. When the pH is neutral, NBs exhibit an electrical charge, and their Zeta potential (ZP) values fall within the range of −17 to −20 mV at a pH of 5.7–6.2 for air NBs, while oxygen NBs display ZP values ranging from −34 to −45 mV at a pH of 6.2–6.4.

The alteration of Zeta potential (ZP) values is commonly attributed to the adsorption pattern and ionization of surfactants at the interface of NBs. This mechanism is extensively discussed. Research has demonstrated that cationic surfactants can yield positively charged bubbles, whereas anionic and non-ionic surfactants facilitate the formation of negatively charged ones. Zeta potential plays a pivotal role in assessing colloidal stability. In the context of a suspended colloidal particle, the zeta potential signifies the electric potential within the interfacial double layer at the position of the slipping/shear plane concerning a point in the bulk fluid distant from the interface. Put differently, the zeta po-

tential represents the disparity in potential between the dispersing medium and the motionless layer of fluid adhering to the dispersed colloidal particles. Direct measurement of zeta potential is not feasible; however, it can be deduced through a theoretical framework, and the electrophoretic mobility of charged entities can be determined experimentally under the influence of an applied electric field. The definition of electrophoretic mobility, denoted as μ_e , and mobility can be calculated from direct experimental observations by measuring time, distance, and voltage using the following equation.

$$\mu_e = \frac{u}{E} \quad (6)$$

In Eq. 6, the parameter u represents the displacement rate of the dispersed particle, and E signifies the intensity of the externally applied electric field. Electrophoretic mobility based on chemical and physical properties can be computed using the formula shown in the following equation.

$$\mu_e = \frac{2\epsilon_r \epsilon_0 \zeta f(\kappa a)}{3\eta} \quad (7)$$

In this context, μ_e is the electrophoretic mobility, ϵ_r and ϵ_0 correspond to the relative permittivity or dielectric constant of the dispersing medium and the permittivity of a vacuum, η is the dynamic viscosity of the dispersing medium at the specific experimental temperature, ζ is denoted as the zeta potential, $f(\kappa a)$ is Henry's function. The latter characterizes the electrophoretic mobility of a spherical colloidal particle when surface potentials are minimal. The surface charge density of NBs is influenced by various factors, including viscosity, bulk solution density, electrolyte concentration, chemical surfactants, pH, and temperature. When gas flow rates are regulated and ample energy or pressure is supplied, the potential values of the bubbles are elevated. Importantly, this outcome is observed regardless of the type of gas.

2.5. Bubble collapsing and free radicals' generation

MNBs' ability to generate strong free radicals like hydroxyl radicals (−OH) is a major factor in their use in wastewater oxidative treatment. These hydroxyl radicals have strong oxidizing power, enabling them to efficiently degrade contaminants that would otherwise be resistant to breakdown under normal conditions. This is especially helpful for breaking down stubborn contaminants, such as organic phenols. Free radicals produced when MBs collapse under a strong ionic field with very high ion concentrations have favourable effects for a variety of technical applications in organic wastewater treatment (Singh et al., 2024). Since radical generation is caused by the buildup of ions around collapsing massive boulders, its mechanism differs from that of cavitation bubbles formed by the impact of ultrasonic waves.

When MNBs collapse under ultrasonic vibrations, bubbles break, releasing free radicals into the atmosphere. During bubble collapse, the potential increases, leading to the production of free radicals. The underlying mechanisms suggested include the generation of free radicals due to the abrupt surge in ion density and the entrapment of surplus ions at the MB interface. At the same time, the abrupt vanishing of the gas-liquid interface due to bubble collapse may also play a role. To put it differently, the collapse of bubbles leads to the vanishing of the gas-liquid interface. Throughout the MNB self-pressurizing process, a notably elevated concentration of charged ions accumulates at the interface, triggering rapid dissolution. This, in turn, instantaneously unleashes chemical energy, generating hydroxyl radicals (OH). The stability and durability of cavitation bubbles are reflected by the efficiency of generating free radicals by the thermally induced breakdown of water molecules. MBs may enhance the generation of free radicals under ultrasonic waves, potentially increasing hydroxyl radical (OH) production.

The amount of free radicals produced when oxygen MBs dissolve depends on the pH of the solution. Specifically, lower pH values increase

the generation of free radicals, thereby enhancing the effectiveness of radical-based oxidation processes. In an acidic environment, ozone NBs are more likely to generate OH than MBs at higher concentrations. This result, in contrast to larger-bubble studies, was observed only when additional initiators were added to generate additional hydroxyls. This makes smaller bubbles, such as NBs, more capable of initiating radical reactions in low-pH environments. The type of gas used to make MB also impacts the quantity of free radicals generated. Oxygen MBs have a higher propensity than nitrogen MBs to encourage the production of -OH radicals. Furthermore, hydroxyl radical production is often stimulated by oxygen MNBs. Because NBs generate reactive oxygen species (ROS), they are likely to have effective cleansing properties. According to the Young-Laplace equation, the internal pressure of NBs is significantly higher than that of the atmosphere. The rupture of these NBs releases more surface energy, which makes it easier for O₂ molecules to become ROS. Furthermore, results demonstrate that oxygen nanoparticles can continue to produce ROS for durations longer than 24 h. Studies have shown that microbubbles can generate hydroxyl radicals during ozonation. These radicals are highly reactive with organic waste and other chemicals in water, making them useful for a wide range of sanitation-related applications. When NBs collapse, reactive oxygen species, or ROS, are released. A significant surface energy release during NB collapse drives electrons into an excited state, which helps divide water molecules and produce ROS. NBs have a promising capacity for efficient sanitation due to their ability to produce ROS. Small-scale, microscopic bubbles may increase the generation of OH• radicals during ozonation treatment. Because of their markedly increased reactivity with organic waste and water chemicals, these radicals can be used in a variety of sanitation applications (Favvas et al., 2024; Zhu et al., 2024). The standard redox potential for OH• radicals is approximately 2.80 V. The elimination of organic pollutants by bulk nanobubble-based advanced oxidation methods is discussed in Table 1.

3. Nanobubbles generation techniques

NBs have been created using a variety of critical techniques, including cavitation, membrane, and electrolysis methods. NBs-generating techniques require certain essential qualities, such as enhanced efficacy, permanence, and simplicity, to be integrated with NBs generators at an industrial level (Ahmad et al., 2018). Several different NB generator models are available on the market at the experimental size. Simple, affordable techniques with pronounced stability and relative ease of scale need to be assessed to evaluate processes for NB production. Several techniques are utilized to produce surface- and bulk-level nanobubbles. If the objective is to create surface nanobubbles, the five methods listed below are the most successful (Lohse and Zhang, 2015). Among them are (i) directly submerging a hydrophobic surface or substrate in water, (ii) electrochemical or photochemical reactions, (iii) increasing the temperature of the substrate after

it has already been submerged in water, (iv) reducing the pressure in a system after a hydrophobic substrate has already been submerged in the liquid phase (water), and (v) solvent exchange. Some of the aforementioned techniques can be used to create bulk nanobubbles. The most effective methods for producing bulk nanobubbles are discussed in the current brief review article, including cavitation, membrane, and electrolysis methods (Ahmed, Shi et al., 2018, Ahmed, Sun et al., 2018). Four main cavitation mechanisms for nanobubble formation are presented in Fig. 3.

3.1. Mechanical methods

3.1.1. Hydrodynamic cavitation (HC)

One of the most common methods for creating tiny gas bubbles is cavitation. When a liquid undergoes a phase transition, cavities form due to sudden pressure drops below specific critical thresholds, typically ranging from -2 to -10 MPa, depending on factors such as liquid properties and dissolved gas content (Wu et al., 2012). Several factors, including surface tension, gas content, and temperature, influence the threshold for cavitation. For example, at higher gas concentrations, the cavitation threshold is lower, thereby promoting bubble nucleation, while increased temperatures reduce liquid viscosity, thereby affecting cavitation behavior (Ahmadi et al., 2013).

When a bubble implodes due to a reduction in local pressure and then reexpands, a significant amount of energy is released into the liquid, a phenomenon known as hydrodynamic cavitation (HC). A drop in static pressure may result from an increase in flow velocity as it passes through constrictive or irregular geometries. As the pressure drops below the local saturated vapor pressure, water cavitation nuclei begin to expand because their internal pressures exceed the surface tension. The expanding nuclei become unstable and collapse as the flow pressure returns. Cavitation occurs in the diffuser section of the venturi after the liquid is pumped from the reservoir into the venturi section. Then, the liquids are pumped back into the reservoir. The procedure will continue for a while until the desired therapeutic result is attained. The Venturi system comprises inlet and outlet tubes, as well as other key components (Ahmadi & Khodadadi, 2013). High-intensity batch agitation can yield NBs with diameters below 500 nm. The prepared solution was poured into the impeller shaft of the cell that produced NBs and swirled at different speeds to prevent dispersion of the added gas. According to another study, hydrodynamic cavitation can produce bubbles with a maximum diameter of 1000 nm (Etchepare et al., 2017). It is one of the most economical and energy-efficient ways to create NBs and offers benefits such as simple equipment and low maintenance costs (Ahmadi et al., 2014). The nanobubble generation technology using the swirl method (spiral flow) is shown in Fig. 4. Due to its ease of scaling up, operation, and control, the venturi-type generator has seen extensive use.

As a result of erosion damage, the investigation of hydrodynamic

Table 1
Removal efficiency of organic pollutants by bulk nanobubble-based advanced oxidation.

Pollutant	Source of gas	Technique involved	Mechanism behind	Removal efficiency (%)	Reference
1,4-Dioxane	Ozone	Nanobubble system	-OH	98.5	(Maie et al., 2020)
Sodium dodecyl benzene sulfonate	O ₂	Nanobubbles or vacuum ultraviolet system	-OH	99.8	(Tasaki et al., 2009)
Dark green Rit dye	Air	Nanobubbles alone; nanobubbles/H ₂ O ₂	-OH, H ₂ O ₂ , O ₂	90	(Bui and Han 2020)
Oxytetracycline	O ₂	Nanobubbles with photodegradation	-OH	98	(Wang et al., 2019)
Methyl orange (azo dye), Benzene, Chlorobenzene	Ozone	Ozone micro-nanobubbles	-OH	>80 for methyl orange >95 for benzene and chlorobenzene	(Xia & Hu, 2018)
Bovine Serum Albumin (BSA)	air	Electrochemically generated nanobubbles	defouling action of nanobubbles	26–34	(Wu et al., 2008)

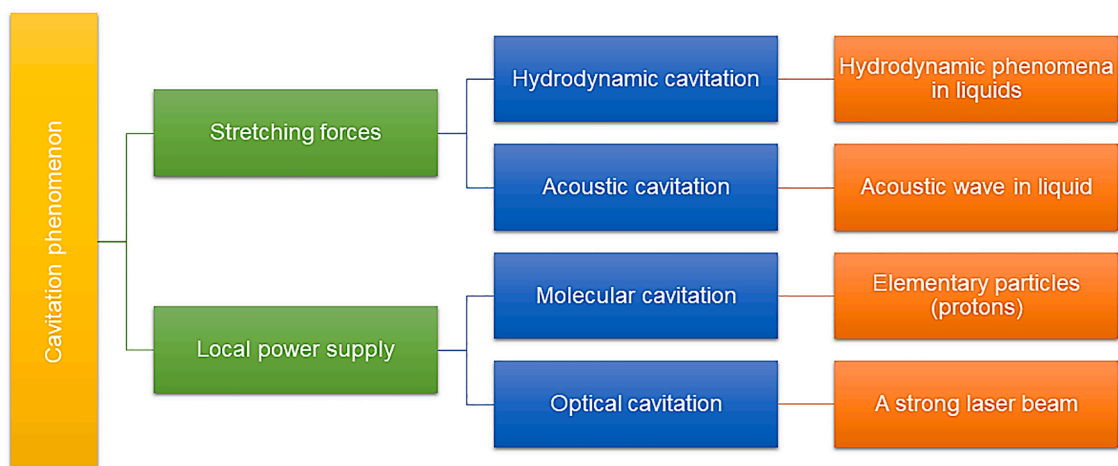


Fig. 3. Four main cavitation mechanisms for nanobubble formation.

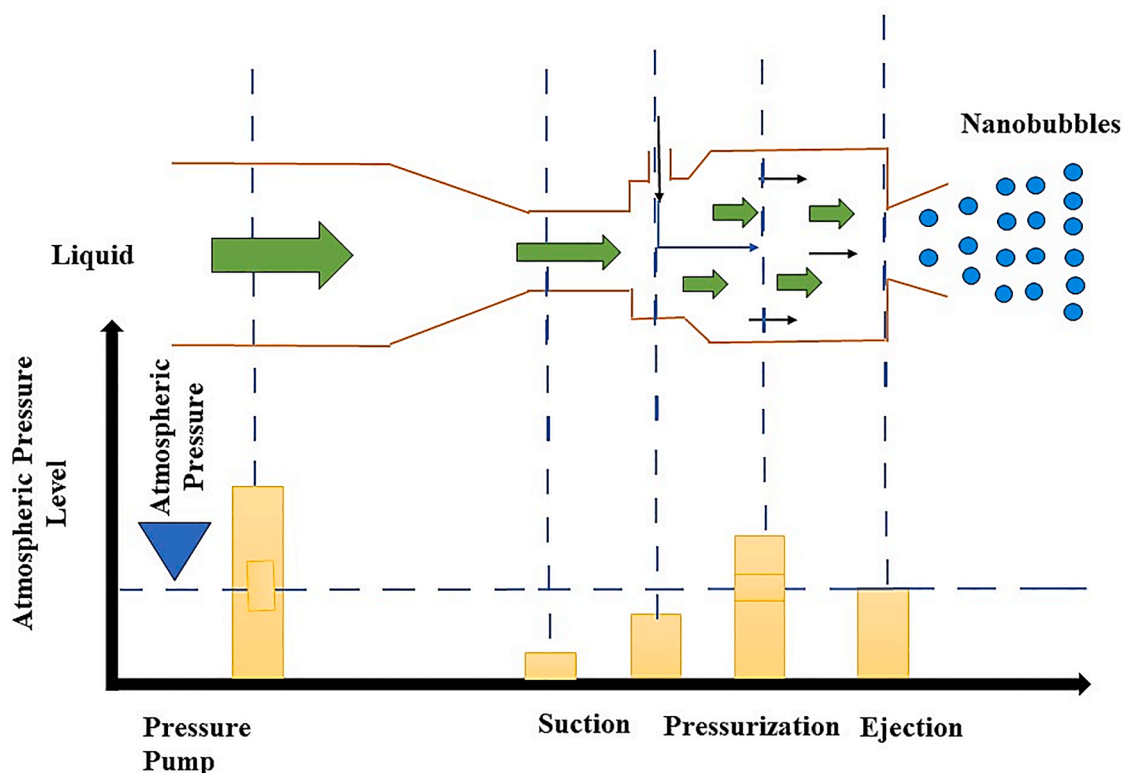


Fig. 4. Nanobubble generation technology by swirl method or spiral flow.

cavitation started around the turn of the 20th century. The large ocean liners Lusitania and Mauretania's propellers suffered serious, catastrophic damage as a result of cavitation, according to Silberrad (1912). Since then, researchers have focused on the detrimental effects of cavitation, including performance losses in various fluid equipment, noise, and erosion damage (Sun et al., 2017b). On the other hand, the first case study on microbial cell disruption with HC was published. Following that, particularly over the last several years, HC applications have attracted attention across a range of fields. The phenomenon of hydrodynamic cavitation is mainly due to the collapse of larger bubbles (1 micron and greater), which generate high-velocity microjets and shock waves that erode propeller surfaces, pump components, and other submerged structures. Extensive studies have attributed such damage predominantly to larger bubbles, as they possess greater collapse energy

and more destructive force upon implosion (Yasui et al., 2018). However, emerging research suggests that nanobubbles (NBs) may also contribute to material degradation through various mechanisms. However, NBs do not collapse as violently as observed for larger cavitation bubbles; their prolonged stability and ability to merge under certain conditions may amplify cavitation effects, thereby influencing surface fatigue over an extended period of time (Takahashi et al., 2021). Albanese et al. (2019), who used HC to increase biochar surface area by up to 120% while maintaining or enhancing its chemical composition, reported the first investigation into the synthesis of nanomaterials using HC. The biochar's increased functionality and porosity were the result of the HC's physical impact and oxidation (hydroxyl radicals). The cost efficiency was also demonstrated to be at least one order of magnitude higher than that of the conventional method, demonstrating the

viability of HC as a substitute strategy for the synthesis of nanomaterials. Since the HC phenomenon is generated by the hydrodynamic cavitation reactor (HCR), which serves as the reaction vessel, the efficiency, viability, and practicality of HC technology depend on how effectively the HCR produces HC. The most crucial issue is to establish new-family HCRs to accelerate the development of HC-based synthetic methods for the industrial-scale manufacturing of nanomaterials.

Based on their mode of operation, HCRs may be broadly divided into two types: non-rotating and rotational. Low-pressure separation regions can emerge in typical conventional HCRs (CHCRs, for example, venturi type and orifice type) when the fluid passes through the contractive part, where static pressure is transformed into kinetic energy (Jančula et al., 2014; Merzkirch et al., 2015). Due to their straightforward design, lack of moving parts, ease of fabrication, and convenience of use, CHCRs have been widely used in previous laboratory research to investigate HC treatment processes (Dular et al., 2016). Studies have also indicated that CHCRs have practical industrial uses (Sun et al., 2020). Recently, a few rotor-stator-type HCRs (R-S HCRs) have been presented in the literature. A circular, cross-sectioned cylinder or disc with many gaps is how R-S HCRs create cavitation (Zupanc et al., 2014). The rotor drives the fluid due to its viscosity, and the flow and rotational directions are the same. The flow creates a low-pressure separation area by punching the rear edge of the gap. When the rotational speed reaches the critical threshold, cavitation bubbles may form. The study provided the efficacy of HCR in eliminating germs (Marálek et al., 2020), biofuel synthesis (Mohod et al., 2017; Chipurici et al., 2019), WAS treatment (Kim et al., 2019, 2020), fibrillation (Kosel et al., 2019), organic wastewater treatment (Zupanc et al., 2014), delignification (Badve et al., 2014), and intensification of biogas production (Patil et al., 2016). Due to the harsh conditions and the hydroxyl radicals produced by HC, effective synergistic interactions between HC and heating, AC, various oxidants, photocatalysts, photolysis, and electrochemical processes have also been demonstrated (Sun et al., 2018). More importantly, it is worth noting that R-S HCRs exhibit promising scalability (Joshi & Gogate, 2019), and their performance can be easily enhanced by increasing their dimensions. This was confirmed by Sun et al. (2018), who found that when the HCR's rotor size was doubled (290–590 mm), heat generation and thermal efficiency increased from 48 to 200 MJ/h and from 82 to 91%, respectively. Even though HC technology has been studied and developed for about 30 years, it has not yet been widely used in industrial applications worldwide. There tend to be several limitations hindering the large-scale adoption of the HC technique, such as the lack of standardized reactor designs, energy consumption, and material degradation from prolonged exposure to cavitation-induced stresses, which can cause wear and tear of system components and increase maintenance costs. The properties of HCRs have seldom been the focus of previous research, which significantly impacts the advancement and utilization of HC technology. Although some researchers have made significant advances in the theoretical (Sarvothaman et al., 2019), computational (Badve et al., 2015), and experimental (Zhang et al., 2018) aspects of HCRs, their cavitation generation mechanism, internal flow fields, external characteristics, and scale-up law remain poorly understood when using experimental flow visualization, particle image velocimetry, and computational fluid dynamics methods, especially true for the R-S HCRs. More importantly, there is no universal design methodology for HCR (such as the scale-up law and optimization technique, theoretical and numerical methods for designing the rotor, stator, and flow route). In the future, it will be necessary to conduct research into the interior fluid field, optimize geometrical shapes, use numerical simulation techniques, and perform dimensional evaluations.

3.1.2. Ultrasonic treatment

Water is treated with ultrasonic waves, which cause microscopic bubbles to form at nucleation sites, grow to approximately resonance size in response to variations in acoustic pressure, and then burst. According to Yasuda et al. (2019), to produce bulk nanobubbles via

ultrasonic treatment, a Langevin transducer connected to stainless steel vibration plates at the bottom of a vessel is required, along with a circulating water bath to maintain the sample's temperature. The transducer is controlled by a signal generator driven by a power amplifier to maintain a constant sinusoidal wave throughout the bubble-creation process. The transducer sonicates ultrapure water during manufacturing, forming submicron bubbles via acoustic cavitation. They experiment with several ultrasonic frequencies, ranging from 22 kHz to 1 MHz, and find a tendency for rising nanobubble concentration with decreasing ultrasound frequency, but the influence of frequency on the mode nanobubble diameter is negligible. They investigate the effect of ultrasonic power on nanobubble concentration and find that it increases with increasing ultrasonic power. According to their findings, the mode diameter of the produced bulk nanobubbles is between 90 and 100 nm under all conditions, and the bubble concentration increases with treatment time, asymptotically reaching $1.5 \times 10^9 \text{ mL}^{-1}$. High-frequency (16 kHz–100 MHz) sound waves, or ultrasound, cause cavitation when applied to a liquid medium. Millions of cavities are produced when ultrasonic waves are transmitted through a liquid, and the local pressure in the rarefaction zone drops below the threshold pressure for cavitation, which is the medium's vapor pressure at the operating temperature. Under pressure changes, sound waves can cause acoustic cavitation in the liquid. Passing sound waves through a static liquid system may change the ambient pressure. The liquid is subjected to mechanical forces from the delivered sound waves, producing alternating cycles of high-pressure (compression) and low-pressure (rarefaction) zones. Cavitation or bubble formation results from a pressure variation whose amplitude is equal to or less than the vapor pressure during the liquid's negative half of the sound cycle. Stable cavitation bubbles and transient cavitation bubbles are two distinct forms of bubble motion. A bubble that exhibits stable cavitation merges and rises to the surface after repeatedly oscillating around its equilibrium location during compression/rarefaction cycles. Over a few further compression and rarefaction cycles, the transient cavitation bubbles expand until they reach the critical size and collapse.

The bubble radius is not proportional to the created sound pressure since this is often a non-linear process. Additionally, the bubble receives sufficient potential energy from the sound wave throughout these multiple growth cycles; as a result, when the bubble bursts, kinetic energy is concentrated. High energy is concentrated in a relatively small volume during bubble collapse, leading to extremely high pressures and temperatures that can erode materials, initiate chemical reactions, and generate radicals (Batagoda et al., 2018). If the pressure is reduced to a level below the typical vapor pressure, it has been claimed that ultrasonic vibrations can create bubbles (Akshiti et al., 2024; Demangeat, 2015). By ultrasonically processing CO₂ gas, NBs with typical sizes of 300–500 nm were created in an aqueous solution. Researchers produced air NBs with a 750 nm diameter that were stable for one hour. Additionally, by using ultrasonic waves after infusing gas under pressure into an aqueous medium to form a gas-saturated liquid, many gas bubbles can be produced. In the lactose solution, CO₂ gas bubbles of the nano- to micron-scale were also created using ultrasonics at a 50% amplitude (Xun et al., 2017). The research found that carbon dioxide NBs might utilise gel-based, low-intensity ultrasonic vibrations (Xu et al., 2016). Horn-type (Jadhav & Barigou, 2020; Nirmalkar et al., 2018a) and bath-type (Nirmalkar et al., 2018a) are the two primary experimental settings for the creation of acoustic cavitation employed for the formation of bulk nanobubbles. An ultrasound probe (ultrasonic horn) is submerged in a liquid. A horn tip that is substantially smaller than the acoustic wavelength emits an acoustic wave (Yasui & Yasui, 2018). An ultrasonic transducer is mounted to the outside of a liquid container for bath-type ultrasound equipment. Additionally, the inner surface of a tiny closed box submerged in the liquid can be used to connect the ultrasonic transducer (Bu & Alheshibri, 2021). For high frequencies between 100 kHz and 1 MHz, which are commonly used in bath-type ultrasonic equipment, a thin piezoelectric plate is typically employed in

conjunction with a vibration plate (Bu & Alheshibri, 2021). Low ultrasonic frequencies (20–200 kHz), which are commonly used in horn-type ultrasound equipment, are better suited to bolt-clamped Langevin-type transducers (BLT). It was observed that bath-type ultrasound equipment, as opposed to horn-type ultrasound equipment, may produce a larger concentration of nanobubbles with comparatively lower power.

3.1.3. Optical cavitation

Short-pulsed (high-intensity) lasers focused on liquids with low absorption coefficients can induce optical cavitation (Padilla-Martinez et al., 2014). When the powerful pulses of a Q-switched ruby laser are directed into a liquid, optical cavitation results. The medium breaks down under such hostile conditions, forming bubbles. Using a fast-revolving mirror camera, these bubble formations can be captured.

3.1.4. Particle cavitation

High-intensity light photons travelling through liquids produce particle cavitation (Poulain et al., 2015). Bubble formation in a superheated liquid causes particle cavitation. The charged particle leaves ionization tracks in the fluid after passing through it for a brief period. The energy of those ions may be transferred to a few quick electrons, which can instantly gain 1000 electron volts of energy in a small area, providing local heating. Therefore, boiling will occur along the track, and small bubbles will form if the liquid is susceptible to superheating due to expansion (Batagoda et al., 2018). It is worth mentioning that the production rate and size of bubbles are greatly influenced by various factors, including the wavelength and intensity of incident photons, the thermophysical properties of the liquid (such as surface tension and viscosity), and the level of superheating achieved during the process. However, in particle cavitation, the type and energy of the ionizing particles also play a critical role in determining bubble nucleation rates and growth dynamics.

Further, the liquid tension induces hydrodynamic, acoustic, and particle cavitation, whereas local energy deposition induces optic and particle cavitation (Batagoda et al., 2018). Contrary to hydrodynamic/acoustic cavitation, controlled bubble production is possible in particle/optical cavitation. It's possible to regulate bubble size and placement inside the liquid. However, because of their higher operating costs, they are used only in laboratory and research investigations and are not commonly seen in real-world applications (Ozonek, 2012).

3.1.5. Surface electrostatic nanobubble formation

Ghaani et al. (2020) developed a revolutionary technique by utilising an electric field to create nanobubbles. A stainless steel container filled with deionized water serves as the experimental setting for this procedure. A specified gas (methane or oxygen) is injected into the container through a linked tube until the water within the container is saturated with gas. The connecting wires at the bottom of the container apply a fixed electric field to the water, with a magnitude of about 12 kV·m⁻¹. According to the authors' theory, areas of negative pressure induced by an electrostrictive force via an electric field result in the formation of nanobubbles in a dielectric liquid. The nanobubbles' mean diameter increases from about 220 nm to 300 nm after four months.

3.1.6. Using graphene oxide sheets

On the surface, gas supersaturation nucleation occurs when two miscible solvents with different gas solubilities are mixed. Jannesari et al. (2018) used this phenomenon to produce bulk nanobubbles. The two miscible solvents are warm water and a NaCl solution saturated with cold nitrogen. Graphene oxide (GO) sheets serve as nucleation surfaces for the formation of bulk nanobubbles. GO sheets can be created using the Hummers' method. A microvortex platform enabled nucleated nanobubbles on the GO sheet surface to split into bulk nanobubbles. The average diameter of the bulk nanobubbles is 545 nm, with a range of 320–920 nm

3.1.7. Shirasu-porous-glass (SPG) membranes

A method that uses a Shirasu-porous-glass membrane was provided to create bulk nanobubbles. A water-SDS solution passes through a tubular glass membrane in the membrane module, the system's primary part, which has submicron-sized holes in it. Pressurized air is delivered to the module outside the glass membrane and forced into the flowing solution by the transmembrane pressure difference, creating nanobubbles. Drag forces detach the bubble from the pore, which is subsequently incorporated into the solution. Bulk nanobubbles, therefore, develop in the fluid. The arrangement produces nanobubbles with a mean diameter of 360–720 nm. A combination of sodium carbonate, calcium carbonate, magnesium oxide, and boric acid is used to create the porous glass membrane. A hydrochloric acid solution is used during the moulding process to create tiny holes on the glass's surface, forming the tubular glass. In comparison to previous approaches, the nanobubbles produced using this technology exhibit better size monodispersity (the degree to which particles (or bubbles) in a given system have a uniform size distribution) with a reported PDI (polydispersity index) typically ranging between 0.1 and 0.3, indicating a relatively narrow size distribution and ensuring enhanced stability in various applications (Kim et al., 2020).

3.1.8. Generation via a nanoporous membrane

Bulk nanobubbles were created using a nanoporous alumina membrane. The nanoholes in the alumina membrane have a mean diameter of roughly 100 nm. Researchers use the anodization procedure as a quick, low-cost, and effective way to create the membrane. They use a nanoporous membrane to inject gas into a cell containing DI water for 1 h at 1.5 atm to create bulk nanobubbles. Bulk nanobubbles are created when the gas squeezes out from the nanopores in DI water after passing through them. This method generates CO₂ bulk nanobubbles with diameters of 50–200 nm. Moreover, the authors employ various gases, including nitrogen, oxygen, helium, and argon, to examine the stability of the bulk nanobubbles. Due to their greater water solubility, they found that, under identical conditions, CO₂ nanobubbles are smaller than those of the other gases. The bulk nanobubble concentration, around 6×10^7 mL⁻¹, is suitable for several in vivo and in vitro biomedical applications. However, as with the other techniques mentioned earlier, the one they provide is unable to accurately control nanobubble diameter. The lifespan and polydispersity index of the created bulk nanobubbles have not been studied. Another popular method for creating NBs is to drive the gas phase through the pores of an applied membrane into a flowing aqueous phase. This is done using a membrane as the medium for liquid and gas dispersion. By infusing pressured gases like air, N₂, and O₂ through ceramic membranes with nanopores, Ahmed, Shi et al. (2018) could monitor the creation of NBs in water. With an increase in air injection pressure from 70 to 400 kPa, they saw that the size of the air NBs fell from 600 to 340 nm.

3.2. Chemical methods

3.2.1. Electrolysis

Another technique employed in recent years is the creation of nanobubbles using an electrochemical cell. The technology consists of two electrodes inserted into a cell and connected to an external power source. When the electrodes are properly voltaged, an electrical current flows from the anode to the cathode, electrolyzing the water in the cell. During electrolysis, oxygen nanobubbles are produced at the anode. Bulk oxygen nanobubbles with a 30 nm starting size were reported to be created by Kikuchi et al. Three days after the bulk nanobubbles form, their final size increases to 250 nm, and then the bubbles' oxygen dissolves them, causing them to disappear eventually.

Electrolysis has been shown to yield NBs with a diameter of approximately 100 nm that were stable for a day (Zhu et al., 2016). Hydrogen and oxygen gases are produced when the electric potential of water is electrolysed. The electrodes produce gas. The generated gas

concentration in the anode and cathode media of the bulk water may exceed the supersaturation threshold, leading to NBs. Another study found that oxygen NBs are more stable for up to 72 h when the bubble diameter is approximately 250 nm. This technique uses electrochemical reactions at electrodes, such as those that occur during the electrolysis of salt solutions, to create nanobubbles. Some electrodes have the potential to produce hydrogen and oxygen nanobubbles when electrolyzing water in the presence of an acid or base. There have been instances of over-saturation incidents during electrolysis involving hydrogen and/or oxygen. As recently reported by Postnikov et al. (2018), bulk nanobubbles with controlled size can be safely and easily produced via alternating-polarity electrolysis of water. In a reservoir of approximately 12 mL, BNBs are produced using a solution of 1 mol/L Na_2SO_4 in distilled water as the electrolyte. Three constantly spaced layers are deposited layer by layer on an oxidised silicon wafer to build the electrodes, which are then immersed in the solution. The chosen concentric electrode configuration results in a higher concentration and more symmetrical dispersion of the NBs.

The square voltage of 11 V pulses of alternating polarity, with amplitude U and frequency f (usually $f = 200$ kHz), is applied via the electrodes to achieve alternating polarity electrolysis. The produced BNBs can be visually spotted above the electrode region using the Schlieren method (Postnikov et al., 2018). The temperature changes, as discovered, result in a distinctive schlieren pattern and offer distinct dynamics. One can detach a limited volume enriched with nanobubbles from the parent cloud and allow it to persist independently. The average size of the bulk nanobubbles generated during the procedure is 60–80 nm, as determined by dynamic light scattering (Postnikov et al., 2018). The nanobubbles are still visible 15 min after the electrical pulses are turned off, but their size has increased to roughly 250 nm. The spontaneous combustion interaction between hydrogen and oxygen in the NBs was responsible for the alteration in the distribution and concentration of NBs during and after the electrochemical process.

3.2.2. Plasma

Plasma was used to create nanobubbles by Sato et al. (2015). One side of a platinum wire electrode used in their experiment is submerged in water, while the other side is wired to a power source. A ground electrode is positioned under the water vessel's bottom, and a platinum ring electrode is attached to the power source. The wire electrode producing plasma emission at its tip is subjected to a current with a voltage range of -3.5 to -5.5 kV and a frequency of 10 kHz. According to their explanation, gas channels along "streamer discharges" generated by underwater plasma emission collapse, forming bulk nanobubbles with a mean diameter of 120 nm and a size distribution of 50–400 nm.

3.2.3. Surface nanobubbles

Investigations of AFM imaging of surface NBs used a manufacturing approach called the solvent exchange technique. When ethanol is applied to a hydrophobic surface and then removed with water, the dissolved gas becomes supersaturated, leading to the nucleation of NBs. Since then, it has become an accepted practice. The saturation values that may be produced are up to three times the equilibrium concentration, according to An et al. (2015); however, its efficacy varies. The surface-nucleating and growing NBs are caused by radiolysis, which is induced by electron beam irradiation (Grogan et al., 2014). According to Loshe et al. (2015), if volume V is in the range of 10–18 L (attoliters), the height H will vary between 1 and 10 nm, and the width L will vary between a few hundred nanometers and a few microns. The number of gas molecules is estimated as $N \sim 10^3$ using the ideal gas law, accounting for the ambient pressure in the NB (which is an overestimate due to Laplace pressure). Based on the Brunauer–Emmett–Teller hypothesis, there are approximately 500 nitrogen molecules in the footprint area $\pi L^2/4$, with a cross-sectional area of 16 nm² (Wang & Jin, 2023). Numerous approaches are available for the surface NB study. AFM and scanning electron microscopy, which offer a high spatial

resolution, are the most accurate. These two methods allow for the observation of a true representation of the formatted surface NBs, with measurements of both shape and size. With a typical optical microscope, only bubbles with a wide lateral diameter of around 1.5 mm may be resolved. By altering the physicochemical characteristics of the studied system, surface NBs are indirectly investigated using methods such as surface plasmon resonance spectroscopy, attenuated total reflection infrared spectroscopy (ATR-FTIR), X-ray scattering (SAXS), and neutron reflectivity. A high-resolution bottom-view image of colored surface nanodroplets can also be obtained using confocal imaging (Zhang et al., 2015). In situ transmission electron microscopy offers excellent spatial and temporal resolution and has recently been employed to characterize the NB nucleation process (Liu & Dillon, 2014). Using a quartz crystal microbalance (QCM), the absorbance at the crystal surface can be quantitatively measured.

4. Factors affecting nanobubble formation

The method of producing nanobubbles is intricate. Multiple factors affect the creation of nanobubbles with complex diameters (Javed et al., 2023). Nanobubbles offer advantages in food preservation and fermentation, but their stability and long-term impact on food quality require evaluation. Their effectiveness varies with temperature, pH, and food medium, as high temperatures and acidic environments can reduce stability. Nanobubbles work best in liquids but have limited penetration in solid foods. While they help retain nutrients and natural flavors, prolonged exposure to reactive gases may alter vitamins and textures. Further research is needed to optimize their stability and assess any residual effects on food over time. The following are the various elements that influence the creation of nanobubbles.

4.1. Temperature and pressure

The production of nanobubbles is greatly influenced by temperature and pressure (Bui & Han, 2015). Temperature and pressure applied during the production of nanobubbles affect their construction and operational environments. As the aqueous phase's surface tension rises, the critical pressure for bubble formation in the hydrodynamic cavitation method will increase accordingly. However, the rise in pressure drop will also increase cavity collapse severity and turbulent intensity (Phan et al., 2020). The size of the created bubbles is significantly influenced by pressure, which has an impact on the nanobubbles' diameter (Kim et al., 2012). Higher pressure has been found to increase gas density, leading to smaller bubble sizes. However, the size of small cavities remained almost unchanged at pressure values greater than 3.5 bars (Temesgen et al., 2017). The mean size increases, and the concentration of bulk nanobubbles decreases as static pressure rises (Tuziuti et al., 2017). According to studies, decompression can result in large bubbles (Arieli & Marmur, 2013). Since temperature influences several fluid physical properties (including vapor pressure, viscosity, surface tension, and ability to dissolve gas in water) that are employed to produce nanobubbles, it also has a significant impact on their formation (Rosa & Rubio, 2018). For instance, a change in temperature will increase vapor pressure and reduce gas solubility in water, leading primarily to the formation of nanobubbles. As a result, as the temperature rises, cavitation will occur at a slower rate (Mancuso et al., 2020). The size of O_2 nanobubbles increases as the temperature is raised from 20 to 40 °C. This is due to an increase in the O_2 concentration gradient between the bulk medium and the bubble interface and a decrease in the dissolved O_2 concentration from 10.5 to 2.5 mg·L⁻¹ (Ahmadi & Khodadadi, 2013). Due to a decrease in solution fluidity caused by lowering the temperature from 65 °C to 50 °C, the concentration of bubbles decreased, while their diameter increased. Reducing the solution's fluidity also decreases the effectiveness of foam production, which has an adverse impact on nanobubble generation (Counil et al., 2022). The ambient temperature can influence the dynamics of bubble collapse,

and raising it can lead to a non-spherical bubble shape with a jet flow during the bubble rebound stage (Phan et al., 2022).

4.2. Gas type and concentration

The gas used to create nanobubbles is also regarded as a crucial factor in determining the development and properties of these nanoscale cavities. The amount of dissolved gas in the aqueous system and the rate of bubble nucleation are related (Bunkin et al., 2021). The relationship between gas molecular weight and rising velocity for bubbles generated from various gases, such as CO₂, air, He, and N₂, was validated using theoretical methods (Temesgen et al., 2017). Bubble development's surface tension, form stability, and tensile strength will all decrease as the solubility of the applied gas increases. Consequently, using gases that are more soluble in liquids can result in the production of more bubbles, as surface tension drops and the nucleation rate increases (Lee et al., 2020). The high dissolved oxygen content may be what keeps the gas concentration low between the bubble boundary and the liquid medium. Liquid nanobubble density and persistence may benefit from this. Yasui and colleagues (2016). The type of gas used also influences mass transfer and stagnation duration; compared with air nanobubbles, oxygen nanobubbles exhibit a longer-lasting dissolved-oxygen enhancement and a higher oxygen-transfer efficiency (Tekile et al., 2016). One potential influence of gas solubility on nanobubble nucleation is possible. Since highly soluble gas molecules are closer to one another in solution, more nucleation sites will result in smaller nanobubbles forming, which will help with nanobubble nucleation during the first cycle's decompression. According to Wang et al. (2019), high gas solubility also results in a greater gas concentration gradient between the solution and the nanobubbles. This could lead to a relatively high gas diffusion rate out of the nanobubbles as pressure rises, resulting in the formation of smaller nanobubbles. The stability of nanobubbles is increasingly influenced by the gas types used in the manufacturing process: O₂, air, and CO₂. This is because the absolute Zeta potential value of O₂ nanobubbles is larger (Phan et al., 2020). The measured zeta potential of O₂ nanobubbles in water falls between −45 and −34 mV, while that of air nanobubbles is between −20 and −17 mV (Oh et al., 2015). According to Phan et al. (2021a), the CO₂ nanobubbles' absolute Zeta potential in water varied from −20 to −27 mV. Repulsive forces and the Zeta potential value govern the stability of nanobubbles. More electrostatic repulsion, caused by a higher absolute value of the zeta potential or by more electrically charged bubble surfaces, inhibits nanobubble aggregation (Nirmalkar et al., 2018a). Apart from the dissimilar Zeta potential values, a portion of the stability discrepancy between CO₂ nanobubbles and air nanobubbles may be explained by the significantly reduced partial pressure and increased solubility of CO₂ in the atmosphere and water, respectively (Xue et al., 2022). It was found that while the gas concentration in the water increased from 4 to 10 ppm, the size of the nanobubbles decreased as the O₂ gas flow rate increased from 0.1 to 0.3 L/min. It is possible to maintain a very small gas concentration gradient between the bubble interface and the aqueous medium due to the high dissolved oxygen concentration. According to Ahmadi and Khodadadi Darban (2013), this could therefore enhance nanobubbles' high density and stability in the bulk liquid.

4.3. Surfactants and electrolytes

The creation, stability, and growth of nanobubbles on the electrode surface depend on surfactants, which function as contamination mimics. Surfactants are used to reduce the driving force required to generate a nanobubble. By lowering the gas saturation levels required to nucleate a nanobubble due to a decrease in the surface tension of the gas–water interface, the generation of nanobubbles rises in the presence of surfactant across all voltages. The stability of the nanobubble on the electrode surface is aided by the permeability of gas molecules within it, which may be affected by a thick surfactant layer (Suvira & Zhang

2021). With the addition of NaCl to the aqueous phase at about 100 mM, ultrafine bubbles could be more effectively stabilized. However, higher concentrations of the salt (>500 mM) tend to accumulate positive ions at the nanobubble interface, decreasing the repulsion force, the absolute zeta potential, and the longevity of the nanobubbles (Uchida et al., 2016). Incorporating surfactant molecules into liquid systems to produce nanobubbles, such as methyl isobutyl carbinol (MIBC) and polyglycol (F150 and DF250), may also enhance bubble stability by creating a protective shell and reducing diameter. With the small amount of anionic sodium dodecylsulfate (SDS) surfactant and NaCl salt, it was discovered that the size of the nanobubbles decreased. The disappearance of CO₂ nanobubbles was caused by the addition of Tween 80, a non-ionic surfactant. Meanwhile, the zeta potential of the little bubbles in the fluid containing the SDS material was more negative. Nanobubbles in SDS 0.0001 also lowered surface tension and slowed the decline in dissolved CO₂ in the monitored solution over the course of storage. Functional substances, such as surfactants, may be crucial for the production of several food products (Phan et al., 2021b). Surfactant molecules clinging to the air–water interface of nanobubbles may provide a protective hydration barrier, increasing nanobubble stability. The size of nanobubbles decreases when an ionic liquid is added to distilled water, followed by sonication of the mixture. Zeta potential values alter when an ionized surfactant is added to a liquid structure that contains nanobubbles or when ionic components are captured in the bubble membrane (Wu et al., 2012). Electrostatic repulsion can hinder the amalgamation of bubbles by attracting ions to the nanobubble-electrolyte solution interface. Electric ions can reduce the thickness of the electronic double layer, thereby increasing the interfacial tension that minimizes bubble size (Sovechles & Waters 2015). Nanobubbles are stabilized by adding minuscule amounts of sodium chloride due to ion shielding (Uchida et al., 2016). Alkyl-trimethylammonium bromide was added to pure water, and sonication was used to reduce the nanobubbles from 750 to 450 nm.

4.4. pH and mono and multivalent salts

The mean nanobubble size increases as pH decreases, while the bubble density decreases. With a drop in pH, the suspension's negative zeta potential becomes less significant and turns positive below the isoelectric point. Due to the negatively charged nature of the nanobubble surfaces in pure water, the adsorption of OH[−] ions results in the formation of an electric double layer surrounding the nanobubbles, as observed around solid nanoparticles (Ma et al., 2022). A slight addition of any valence salt results in a significant reduction in bubble number density and a sharp increase in the mean bubble diameter. In the case of a monovalent salt, the negative zeta potential is significantly reduced but remains negative, whereas in the case of a divalent salt, it is reduced to zero, and in the case of a trivalent salt, it transforms to positive at the greatest concentration. For increased salt valence, the electric double layer around the nanobubbles degrades (i.e., the Debye length shortens). The co-ion-induced electric double layer is screened as a result of the salt addition. As a result, the external negative electrostatic pressure drops, leading to a pressure imbalance at the nanobubble's interface and subsequent expansion (Nirmalkar et al., 2018b).

5. Applications of nanobubble technology

Nanobubble technology is one of the most recent environmentally sustainable technologies. While nanobubble technology in the food industry has gained significant attention, its relevance extends to different fields, including wastewater treatment, agriculture, biomedical applications, and industrial cleaning. In the process of water treatment, NB's increase the efficiency of oxygen transfer and pollutant degradation. In agriculture, it improves soil aeration and plant growth. Biomedical applications use the nanobubble technique for efficient drug delivery and therapeutic treatments, while NB is used in industry for surface cleaning

and to enhance chemical reactions. In healthcare, NBs are used as contrast agents to enhance ultrasound imaging (Jiang 2024). Liu et al. (2019) developed nanobubbles incorporating two sequential lipophilic dyes by integrating fluorescence resonance energy transfer (FRET) with bioluminescence resonance energy transfer (BRET). Their study demonstrated that ultrasonic contrast-enhanced imaging with BRET–FRET nanobubbles enabled high spatial resolution visualization of the microvasculature in perfused tissue. Sanlier et al. (2019) designed an innovative dual-drug delivery system utilizing nanobubbles for targeted therapy against non-small cell lung cancer. This system features both magnetic targeting and ultrasound responsiveness. Nanobubble-assisted extraction is an innovative technique that enhances extraction processes, often in combination with ultrasound. Compared to traditional methods, nanobubbles (NBs) offer several advantages, including their gentle agitation, which preserves both the extraction matrix and the target compounds (Javed et al., 2023). The integration of antibacterial zein/thymol nanoparticles, dispersed via nanobubble technology, enhances the functional properties of gelatin films (Yan et al., 2022). Delayed quality deterioration of bananas using NB technology (Pongprasert et al., 2020). Injecting nanobubbles (NBs) into milk before ultrafiltration can reduce viscosity, enhance the removal of non-protein components, and enable spray drying at higher solid concentrations (Amamcharla et al., 2021). Although comprehensively discussing all applications is beyond this review's scope, it is essential to acknowledge the versatility of nanobubble technology before narrowing it to food-related uses. While nanobubbles exhibit significant stability due to their high internal pressure and surface-to-volume ratio, their lifespan still varies depending on factors such as the liquid medium, gas type, and application-specific conditions (Zhang et al., 2023). For example, in the food industry, nanobubbles typically need to remain stable for a long time to influence texture, aeration, or dispersion in emulsions and gels. However, its application in wastewater treatment requires short-lived bubbles that can rapidly release the oxygen to enhance the degradation processes. Thus, the distinction helps reconcile debates about NB stability by considering its function-specific requirements rather than assuming uniform behavior across all the applications it provides. Table 3 presents various types of nanobubbles, their mechanisms of action, and their applications in food processing operations. Nanobubbles offer a highly effective and eco-friendly alternative to traditional food preservation and fermentation methods. Their ability to enhance gas solubility, reduce microbial contamination, and improve fermentation efficiency makes them superior. In food preservation, they extend shelf life by reducing oxidation and disrupting bacterial biofilms without altering taste or quality. In fermentation, they boost microbial activity, enhance gas transfer, and stabilize pH, resulting in faster, more controlled processes. Compared to conventional methods, nanobubbles provide stronger antimicrobial effects, higher efficiency, and lower environmental impact, making them a promising innovation in the food industry.

5.1. Nano bubble assisted freezing/crystallization

There are numerous uses for freezing as a food preservation technique in the food industry. NB-assisted freezing is a recent development in this area. Investigations were conducted into the combined impact of NBs and ultrasound on the freezing of various meals. Pre-introducing stable NBs and using variable ultrasound frequency considerably improved the efficiency of freezing dense foods, highlighting the food industry's enormous potential. A separate investigation examined how the presence of micro- and nanobubbles influenced crystal growth in different liquids, such as sucrose, during ultrasound-assisted freezing. The results proved the feasibility of this approach by showing that adding MNBs in conjunction with ultrasound-assisted freezing increased the freezing rate.

The acceleration of freezing due to the combined effects of NBs and ultrasound can be attributed to nucleation and heat transfer. NBs act as

nucleation sites, reducing the energy barrier to ice crystal formation, leading to a higher probability of ice formation at lower supercooling levels. Additionally, ultrasound-induced cavitation generates fluctuations in localized pressure and microstreaming, thereby enhancing mass and heat transfer. The interaction between the ultrasound and NB techniques increases nucleation sites while improving disruption of the boundary layer around the freezing medium, facilitating more efficient removal of kinetic energy and accelerated freezing.

According to research, a straightforward yet useful method for managing the freezing of food is gas infusion into liquid foods (Tian et al., 2021). The use of NB-assisted crystallization is another innovative technique in the food sector. Larger ice crystals can be produced by using these advanced methods to prevent accumulation on the surface of frozen food. They also demonstrated how cavitation can efficiently increase the freezing rate (Qi et al., 2023). Bubbles already present could cause a nucleation effect similar to ultrasound. According to a study, lactose crystallization can be positively altered by adding gas NBs. Carbon dioxide gas can significantly increase the size, rigidity, and amount of fat crystals in milk. According to a study, butter made from carbonated dairy cream has better physical characteristics. Additionally, the ultrasound-assisted freezing of the maltodextrin solution used micro-nano bubbles. The outcomes showed that the addition of NBs lengthened the crystal development and nucleation times.

5.2. Foam fractionation of protein

Because of their substantial specific surface area and effective liquid-phase retention, nano-bubbles (NBs) have the potential to offer greater advantages in food liquid foaming. The spray-drying process during coffee production produced 100–200 nm nanoscale bubbles. This method preserved the coffee froth and maintained the foam structure (Deotale et al., 2020). On a saturated solid surface, quasi-2-dimensional micro- and nano-foams are generated. Foam that is nearly two-dimensional can occupy more than 80% of a flooded solid surface. According to an alternative study, the hydrophobic protein can be extracted through the utilization of nano-bubble (NB) technology, obviating the need for chromatographic processes. This approach could potentially be extended to purify various proteins (Yan et al., 2022). Infusing gas into food substances offers numerous advantages, such as enhancing food texture, mouthfeel, and sensory attributes. Illustrations encompass a wide array of carbonated beverages, cotton candy, and whipped creams. Through the application of nanobubble-assisted technology, the sensory characteristics of specific foods, including flavor, color, and taste, can be modified. Nano-bubbles have a higher surface area and a lower pH, which contribute to a gentle sensation when the minute food bubbles interact with the tongue.

5.3. Films/gels

Several techniques, such as ultrasound, electrolysis, and high-pressure homogenization, can be employed to generate nano-bubbles (NBs) within food films. Adding these bubbles increases the number of film surfaces, thereby strengthening the film's mechanical resistance. Furthermore, the large surface area relative to the volume of these bubbles may reduce the film's permeability to water vapor, thereby increasing its effectiveness as a moisture barrier. Another important characteristic of NBs' ability is their capacity to alter the film's surface tension. Nanobubbles can alter the film's wettability and surface adhesion by altering surface tension. Because the film must adhere to the food's surface to prevent contamination or moisture loss, this feature can be particularly helpful in developing food packaging materials. Table 2 provides a detailed discussion of the potential applications of nanobubbles in various culinary and non-food industries. Make food products easier to handle by taking advantage of nano-bubbles' (NBs) viscosity-reducing effect. By altering the liquid's physical properties and reducing friction, bulk nanobubbles can increase the liquid's molecular

Table 2

Potential applications of nanobubbles in various industries.

Scientific area	Application	Reference
Medicine	Contrast agents for ultrasonic imaging	(Cheng et al., 2019)
	Treatment of cancer	(Lukianova-Hleb et al., 2014)(Gulafsha & Anuroopa, 2019)
	Dentistry	(Thakur et al., 2017)
Agronomy	Drug, oxygen, and gene delivery	(Rebelo et al., 2016)
	Malaria detection	(Liu et al., 2019).
	Growth of plants	(Klintham et al., 2018)
	Development of cost-effective bio-fertilizers	(Seemakram et al., 2026)
	Control of fungal diseases	(Liu et al., 2016).
Wastewater bioremediation	Positive effects on Vegetable seed germination	(Ebina et al., 2013)
	promote the growth of plants, fish, and mice	(Minamikawa et al., 2015)
	Irrigation with NB water can mitigate both CH ₄ emission and Arsenic dissolution in flooded paddy soil.	(Temesgen et al., 2017)
	Contaminant removals from water and wastewater.	(Tsai et al., 2007)
Groundwater remediation	cost-effective treatment of chemical-mechanical polishing wastewater	(Hu et al., 2018)
	significantly improve gas concentration and provide a continuous gas supply	(Li et al., 2013)
	Enhance the oxygen transfer efficiency from inner bubbles to outer water, which may greatly enhance aerobic bioremediation in groundwater	(Bai et al., 2022)
Land Remediation	MNB aeration is an effective treatment to remediate landfill leachate-contaminated groundwater.	(Sha et al., 2020)
	Land remediation from heavy metals and minerals like arsenic, nitrogen, and phosphorus.	(Batagoda et al., 2019)
Sediment Remediation	Remediation of heavy-metal-contaminated river sediments, such as chromium	(Váfara-García et al., 2026)
Other biomedical applications	Treatment of diabetes, atherosclerosis, thromboembolic diseases, Parkinson's disease, and Alzheimer's disease.	(Váfara-García et al., 2026)
Floatation	Extraction of minerals, phosphates, or coal from undesirable impurities.	(Maoming et al., 2010)
Surface cleaning – antifouling	Surface cleaning, membrane defouling, and prevention of fouling.	(Zhu et al., 2016)

mobility (Liu et al., 2013). Thus, the liquid's total viscosity may decrease due to the presence of nanobubbles (NBs). Researchers added micro- and nano-bubbles to a milk protein solution, a liquid food, before subjecting it to membrane filtration, evaporation, and spray drying (Amamcharla, Li, & Liu, 2017). It's well known that high-viscosity materials limit the efficiency of liquid food production operations by increasing the energy or operating expenses required to force liquids through manufacturing equipment. For example, in the manufacturing of dairy products, increasing the protein content of milk can cause membrane fouling during membrane filtration, and adding chemical additives to regulate flow or diluting milk to lower its viscosity can negatively affect other aspects of the liquid food. The liquid dairy product is treated with tiny bubbles, with an average diameter of 100–5000 nm, to concentrate and standardise the milk proteins before ultrafiltration (Amamcharla et al., 2017). According to Amamcharla et al. (2017), micro- and nano-sized bubbles that are introduced into aqueous solutions—especially in liquid dairy products that include charged particles like milk proteins—come into contact with the charged surfaces of suspended proteins. The lowering of liquid viscosity is believed to be facilitated by this interaction. Small bubbles like these act as a screen between the

milk protein particles, dispersing them and preventing clumping. Viscosity levels significantly decreased with the addition of nano-bubbles (NBs) to their system. The viscosity values decreased by around four-fold, for example, in the tested milk solution with a total solid content (TSC) of 15% and in condensed milk with a TSC of 54%. At a shear rate of 50 (1/s), they specifically reduced from 0.016 to 0.004 Pa s and from 0.4 to 0.1 Pa when tiny bubbles were introduced, the whey protein concentration in the ultrafiltration process's retentate increased by nearly twice as much as in the control group (Amamcharla et al., 2017). The extraordinary mass transfer properties linked to minuscule bubbles (Ghadimkhani et al., 2016) may improve the sensory qualities of food and drink products. Furthermore, this attribute may also have a role in the possible decrease in liquid flux viscosity, which could improve the effectiveness of different food processing techniques (Amamcharla et al., 2017).

5.4. Enhancing the texture characteristics and sensory qualities of food

The process of aerating food involves adding enough air or gas to the food, which can improve its texture, flavour, digestibility, and sensory qualities, among other aspects (Saint-Eve et al., 2010). Common aerated meals include whipped cream, cotton candy, and fizzy drinks. Similar functions can be obtained with emulsions by introducing micro- or nano-sized ultrafine gas bubbles into food products coated with edible emulsifiers. This approach enables the regulation of flavor and color release in food by using suitable activation methods, such as heat or pressure. Incorporating minuscule bubbles can help achieve a more health-conscious product with reduced calorie intake while maintaining comparable taste. This is grounded in the understanding that particles smaller than 10 µm evade individual detection, and that the distribution of air bubbles reduces the energy content per unit volume of food (Niranjan & Silva, 2008). Furthermore, owing to the carbonic anhydrase enzyme's ability to augment the movement of gases such as CO₂ within champagne, the interaction of small bubbles with the tongue might intensify the "tingling" perception of the beverage. This sensation arises from the enzyme-facilitated conversion of CO₂ into H₂CO₃ upon contact. However, the tingling sensation is typically attributed to bubbles larger than 1 micron, not nanobubbles. While it is worth noting that MBs and NBs share certain applications, it is not yet established that nanobubbles explicitly contribute to sensory enhancements. If explored in the future, nanobubbles could offer opportunities for textural and sensory modification in aerated foods, but this remains an area of further investigation.

5.5. Enhancing the nutritional value of food for health benefits

The remarkable antioxidant, anti-apoptotic, and anti-inflammatory properties of hydrogen gas, which have the potential to protect cells and organs, have recently attracted interest for health-oriented applications of nanobubbles (Huang et al., 2010). While the consumption of hydrogen-enriched water is considered a safe and feasible method of hydrogen intake, the gas's solubility in water is limited to approximately 1.6×10^{-4} g in 100 g of H₂O at 20 °C (Safonov & Khitrin, 2013). However, due to the gas-enhancing ability of nano-bubbles (NBs) to increase solubility within aqueous solutions, it becomes possible for water to contain elevated levels of hydrogen stored within nanoscale cavities. In the research undertaken by Safonov and Khitrin (2013), tangible evidence was obtained suggesting that water retained a higher concentration of dissolved hydrogen than would be anticipated based on Henry's law. This finding suggests a substantial likelihood of the formation of hydrogen nanobubbles (NBs) within water saturated with gas, leading to gas concentrations exceeding the equilibrium level. According to Thomson et al. (2016), a continuous supply of oxygen is crucial for maintaining life, as a fall in tissue oxygen tension (hypoxia) can result in mitochondrial dysfunction and cellular damage. Ebina et al. (2013) reported a significant increase in oxygen content, from 7.7 mg·L⁻¹ in regular water to 31.7 mg·L⁻¹ in water containing oxygen nanobubbles

Table 3

Various types of nanobubbles used in food processing applications.

Nanobubble Type	Method of Action	Application in Food Processing	References
Oxygen Nanobubbles	Enhanced oxygen delivery due to smaller size and stability	- Extending shelf life of fresh produce - Enhancing the texture and flavor of baked goods - Preventing oxidation in packaged foods - Improving the fermentation process in brewing	(Phan et al., 2020)
Nitrogen Nanobubbles	Reduced foaming and improved stability in emulsions	- Reducing foaming in dairy products - Enhancing stability of emulsions - Controlling the texture of frozen desserts	(Javed et al., 2023)
Carbon Dioxide Nanobubbles	Enhanced carbonation and pH control	- Carbonation of beverages - Preserving the color and texture of fruits and vegetables - Reducing microbial growth in packaged foods	(Phan et al., 2021a; Phan et al., 2024a; Phan et al., 2024b)
Hydrogen Nanobubbles	Antioxidant properties and improved stability	- Antioxidant properties in food and beverages - Enhancing stability of fats and oils - Reducing oxidation in packaged snacks - Improving the quality of cooking oils - Enhancing flavor and aroma of culinary oils	Zhao et al., 2023; Čolić et al., 2024
Ozone nanobubbles	Disinfection applications	- Drinking water treatment - They demonstrate antimicrobial properties - penetrating the complex structures of fruits and vegetables compared to conventional ozone treatments. - non-chemical alternative for disinfection and preservation	(Seridou & Kalogerakis, 2021; Batagoda et al., 2018)

(O₂ NBs). The same authors demonstrated that introducing air and O₂ NBs had the potential to stimulate the growth of mice, fish, and plants. Also, data indicate that drinking water infused with O₂ NBs decreased the amount of calcium oxalate deposits in mice's kidneys (Noguchi et al., 2017). Hypoxic tissues can receive oxygen from O₂ NBs, as O₂ is highly soluble in solution. The benefits of oxygen nano-bubbles (NBs) on bone metabolism were noted in a study conducted by Noguchi et al. (2017). According to the researchers, these nanoscale oxygen bubbles may also be able to prevent bone loss in mice. At 4 °C, these oxygen nanocarriers (NBs) were stable for 70 days, with an approximate size of 200 nm.

5.6. Sterilizations using NB treatment

Sterilization methods commonly employed in the food industry often encompass heating and the application of chemical agents. Nevertheless, excessive heat can degrade quality, affecting attributes such as appearance, texture, taste, and nutritional content. Additionally, the presence of chemical residues may raise concerns about safety and overall quality. Consequently, an alternative sterilization approach that doesn't rely on thermal or chemical treatments is essential, particularly for fresh food items, given their limited capacity to withstand heat and chemical exposure. Furthermore, this approach must exhibit reduced environmental impact and minimize health risks. When applying NB treatment for sterilization, a biocidal gas is often introduced. For instance, in an experiment involving oyster samples inoculated with feline calicivirus (used as a surrogate for norovirus), both ozone bubbling and ozone nanobubble treatments inactivated over 99% of the virus after 12 h of treatment. In contrast to ozone bubbling treatment, the research showed that ozone microbubble (MB) therapy was effective in managing *Fusarium* spp within hydroponic systems. In subsequent studies conducted in 2009 by Takagi et al. (Takagi et al., 2009) it was shown that ozonated water (with ozone concentrations of 10–12 ppm, nanopico ozone water) reduced foot-and-mouth disease.

Furthermore, this treatment maintained disinfectant effects for up to 60 min after generation against *Salmonella Enteritidis*. Introducing CO₂ nanobubbles (NBs) into pressurized water can significantly reduce the microbial content of the water. Soli et al. (2010) found that effectively decontaminating fresh food could be achieved through a combination of a pre-treatment with air nanobubbles (using a sucrose fatty acid ester surfactant) and a subsequent treatment with slightly acidic hypochlorous water. An investigation by Sharma et al. on the influence of fluid shear and nano-bubbles on bacterial detachment from surfaces demonstrated that incorporating nano-bubbles into the flow enables the detachment of persistent adherent bacteria that would remain attached

under the effect of flow alone. However, it should be noted that the effectiveness of nano-bubble treatment diminishes for larger bacterial entities, such as adherent co-aggregates.

5.7. Seed sprouting

Another captivating application of nano-bubbles (NBs) is their potential to enhance seed sprouting. As outlined by Liu et al. (2014), nanobubbles have the capability to enhance the production of OH⁺ radicals within barley seeds during germination, thereby contributing to the elongation and expansion of cells. Liu et al. (2015) also conducted a thorough investigation into the role of NBs in producing reactive oxygen species (ROS) and their effect on seed sprouting. When exposed to air and nitrogen nano-bubbles (NBs) with an average size of about 110 nm, barley seeds showed rapid growth, increasing by 58% after 17 h of testing. By contrast, the growth rate increased by 28% after treatment with filtered water. Furthermore, barley seeds treated with a water-containing gas mixture NBs were found to have significantly larger amounts of superoxide radicals (O₂^{•-}) than seeds immersed in distilled water. Ahmed, Shi et al. (2018) found that a variety of plant seeds, including tomatoes, carrots, fava beans, and lettuce, showed improved germination rates in NB-infused water, outperforming those in ordinary tap water by a margin of 6–25%. After 37 days of growth, plants grown in water containing nitrogen nanobubbles (N₂ NBs) had 12 leaves, compared to only 6 on plants grown in regular water. According to Liu et al. (2015), these investigations clearly indicate that nano-bubbles (NBs), which can generate moderate levels of exogenous active oxygen radicals, significantly impact the germination process.

6. Challenges and future work

A major hurdle resulted from the inherent instability of nanobubbles in food systems. Nanobubbles have a tendency to coalesce and disappear quickly, resulting in poor effectiveness. The possibility of developing stabilizing agents or encapsulation technologies to extend the longevity of nanobubbles in food matrices should be explored further. Although nanobubble technology demonstrates potential on a lab scale, it is difficult to scale up production for industrial applications. Scalable production methods should be investigated, and the feasibility of integrating nanobubble technology into the food manufacturing sector should be further analyzed, including its economic implications. Accurate characterization of nanobubbles is needed to understand their behavior and optimization methods. Given the importance of real-time nanobubble monitoring, high-resolution microscopy and spectroscopy

could be developed and applied to study nanobubble size distribution, zeta potential, and stability in complex food matrices. Numerous applications of nanobubbles in food processing are being actively explored, such as food preservation, flavor enhancement, and nutrient delivery. Domain-specific requirements and challenges in each application area need to be analyzed to enable the formulation of nanobubble suspensions. Safety evaluation and compliance with food regulatory requirements are critical for any novel food technology. Health and Safety Concerns of Nanobubble (NB) Technology. While NB technology benefits food processing, concerns include food safety risks (potential residues, structural changes), occupational hazards (gas inhalation, equipment safety), regulatory uncertainty (lack of global standards), and microbial/chemical risks (pathogen control, reactive compounds). Further research is needed to ensure safe industrial application. Moreover, future research should focus on comprehensive studies of nanobubbles' safety and toxicity, their environmental impact, and interdisciplinary approaches to the technology to achieve regulatory approval. Key focus areas for nanobubble (NB) applications involve developing standardized generation protocols, refining bubble characteristics, evaluating storage impacts, improving crystallization, lowering viscosity for drying, analyzing sensory attributes, and utilizing NBs as carriers for hydrophobic substances. NBs have promising applications in water treatment, mineral flotation, and drug delivery. Their properties support environmental sustainability by enhancing disinfection and pollutant removal while reducing chemical use. Further research is needed to optimize and automate NB generators for large-scale industrial and agricultural use. Nanobubble (NB) technology offers significant potential in food processing by enhancing gas-liquid phase interactions, improving texture, and removing contaminants with minimal chemical use. It also provides a cost-effective solution for viscosity control and material extraction without the need for emulsifiers. Further research is needed to optimize NB interactions, sustainable generation, and industrial-scale applications. More specifically, research programs can target the use of interdependent emerging technologies, such as nanotechnology, microfluidics, and artificial intelligence, to develop innovative processing and manufacturing solutions. Not only do these approaches extend the current technology's applications, but they can also contribute to the further growth of research in the field through established collaborations.

7. Conclusion

The review highlighted the significant potential of nanobubble technology in several domains owing to its distinctive characteristics. Nanobubbles have the potential to optimize water treatment by increasing dissolved oxygen concentration, facilitating contaminant removal, and aiding in the oxidation of pollutants. Food quality, texture, and flavor may all be enhanced with nanobubbles. In addition to this, they can be used for sanitation, flavour extraction, and food preservation. With their ability to remove contaminants more effectively and make surface cleaning easier, nanobubbles hold the potential to improve cleaning operations. NB technology enhances efficiency, reduces costs, and improves product quality, making it a promising investment. It lowers chemical and energy usage, improves yield and food preservation, and supports sustainability. While initial equipment costs and scalability challenges exist, long-term benefits include cost savings, reduced waste, and increased market demand for eco-friendly solutions. Further research and standardization will be crucial for large-scale adoption. Purification of groundwater, wastewater treatment, and mitigation of environmental contamination are among the environmental remediation tasks for which nanobubbles are employed. While nanobubbles exhibit remarkable stability due to their high internal gas pressure and reduced buoyancy, their long-term persistence can be influenced by external factors, such as pressure, temperature, and interactions with other substances. The versatility and promise of nanobubbles in various industries are being continuously explored through

research and development. Even if many applications show promise, more studies are needed to improve their manufacturing, durability, and integration into real-world scenarios.

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