MICROBUBBLE TECHNOLOGY FOR THE PRESERVATION OF VEGETABLES AND FRUITS: A COMPREHENSIVE REVIEW

ABSTRACT

Fruit and vegetable postharvest losses present serious obstacles to environmental sustainability, economic stability, and food security. Conventional preservation techniques, such refrigeration and chemical treatments, frequently fall short in preserving the quality of fruit and extending its shelf life. Microbubble technology provides a novel, environmentally friendly solution with its small gas bubbles (less than 200 microns) and high surface area-to-volume ratios. By enhancing gas dissolution, microbial inactivation, and pollutant removal, these bubbles improve washing, disinfection, and storage. Microbubble treatments with ozone, carbon dioxide, and hypochlorous acid have demonstrated encouraging outcomes in terms of prolonging freshness, maintaining nutritional value, and lowering chemical usage. Microbubble technology offers a cost-effective and environmentally friendly substitute for traditional preservation techniques, notwithstanding issues with scalability, pricing, and regulatory permissions. Future research should focus on optimizing its integration with other techniques to enhance its commercial viability and effectiveness in food preservation.

Keywords: *Microbubble technology, postharvest preservation, fruit and vegetable storage, microbial inactivation, ozone microbubbles, sustainable food preservation, food safety.*

1. INTRODUCTION

Fruit and vegetable postharvest losses are a major global problem that have an impact on the environment and economies. Despite their widespread use, traditional preservation techniques such chemical treatments and refrigeration frequently lack sustainability and efficacy (Bui, Nguyen, & Le, 2022). These techniques might not always be adequate to minimize environmental effect, preserve crop quality, or lessen spoiling.

Microbubble technology is a relatively new concept that has drawn interest from both industry personnel and researchers. Because of their small size (less than 200 microns in diameter), microbubbles have special physicochemical characteristics that make them ideal for preservation procedures (Agarwal, Ng, & Liu, 2011). These tiny bubbles can interact with generate surfaces in ways that are not possible with conventional techniques because of their vast surface area and high mass transfer efficiency.

The potential of microbubble technology to completely transform postharvest procedures has been demonstrated by recent developments. Microbubbles have been shown in studies to greatly increase the effectiveness of cleaning, disinfecting, and storing perishable fruits and vegetables (Takahashi et al., 2023). Microbubbles improve the cleaning procedure and aid in the more efficient removal of impurities, making the food safer to eat. Their capacity to improve disinfection also results in a decrease in dangerous germs, which prolongs the fresh produce's shelf life.

The benefits don't stop there. Microbubble technology can also optimize storage conditions, helping to maintain the nutritional and sensory qualities of fruits and vegetables for longer periods. This not only reduces food waste but also supports a more sustainable and eco-friendly approach to food preservation.

2. PRINCIPLES OF MICROBUBBLE TECHNOLOGY

Microbubbles are gas bubbles with dimensions usually smaller than 200 microns. Their special qualities are the foundation of microbubble technology. Because of their unique properties, these microbubbles are very useful in a variety of applications, including fruit and vegetable preservation.

One of the standout features of microbubbles is their high surface area-to-volume ratio. This characteristic allows for a greater interface between the gas and liquid phases, facilitating improved mass transfer processes. Additionally, microbubbles possess prolonged stability in liquids, meaning they can maintain their structure and effectiveness over extended periods (Tsuge, 2015). This stability is crucial for consistent and reliable performance in preservation processes.

Another key property of microbubbles is their enhanced dissolution of gases. This means that gases within the microbubbles can dissolve more efficiently into the surrounding liquid, contributing to improved oxidation and other chemical reactions. The cavitation effects produced by microbubbles further enhance their preservation capabilities. Cavitation refers to the formation and collapse of bubbles, which generates localized high temperatures and pressures. These conditions can lead to microbial inactivation, making microbubbles an effective tool for reducing spoilage and extending the shelf life of fresh produce.

The generation of microbubbles can be achieved using various methods. Cavitation-based techniques utilize ultrasonic waves or hydrodynamic forces to create microbubbles. Porous membrane dispersion involves passing gas through a membrane with tiny pores to produce microbubbles. Fluidic oscillation generates microbubbles by oscillating the flow of gas and liquid through a specific configuration (Wu et al., 2019).

Recent studies have also highlighted the role of nanobubbles, which are even smaller than microbubbles, typically less than 100 nanometers in diameter. Nanobubbles offer greater stability and enhanced microbial reduction potential compared to microbubbles. Their minute size allows them to remain stable in liquids for longer periods, and they can penetrate deeper into produce surfaces, providing more thorough cleaning and disinfection (Zhang et al., 2021).

These principles underscore the potential of microbubble and nanobubble technology to revolutionize the preservation of fruits and vegetables. By leveraging their unique properties, these technologies can offer more effective, sustainable, and environmentally friendly solutions to postharvest challenges.

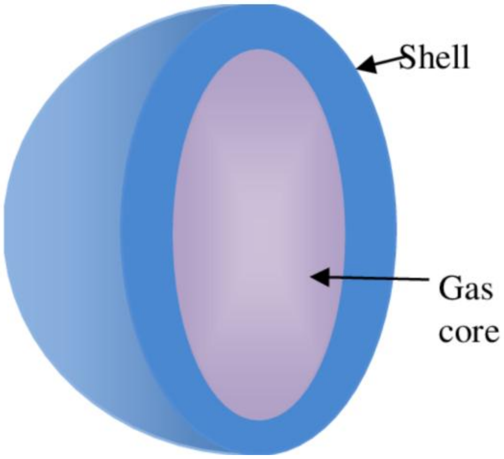

Fig 1. Diagram showing the different layers of a microbubble, the gas core has a radius typically between 0.58 µm and the shell thickness is between 1-100 nm. [Harfield, C. *et al.* (2013)]

3. MECHANISMS OF MICROBUBBLE ACTION IN PRESERVATION

Oxidation and Reactive Oxygen Species (ROS) Production: Microbubbles containing oxygen or ozone are capable of generating reactive oxygen species (ROS), such as hydroxyl radicals and singlet oxygen. These ROS are highly reactive and can effectively inactivate spoilage microorganisms by damaging their cellular components. This mechanism ensures that fruits and vegetables remain fresh for longer periods. Research by Nakabayashi & Kobayashi (2021) and Takahashi et al. (2023) has demonstrated the efficacy of ROS in microbial inactivation, highlighting the potential of microbubble technology in enhancing food preservation processes.

Cavitation Effects: When microbubbles collapse, they induce localized high temperatures and pressures, a phenomenon known as cavitation. These extreme conditions create shock waves that can disrupt microbial cell membranes, leading to the inactivation of spoilage-causing microorganisms. This process ensures that the produce is free from harmful pathogens. Wu et al. (2019) have documented the significant impact of cavitation effects on microbial inactivation, showcasing the potential of microbubbles in maintaining the safety and quality of fresh produce.

Mass Transfer Enhancement: Microbubbles improve gas solubility in water, which enhances the oxygenation of the surrounding liquid. This increased oxygenation helps extend the freshness of fruits and vegetables by reducing the rate of anaerobic respiration and slowing down spoilage processes. Tsuge (2015) and Zhang et al. (2021) have highlighted the benefits of improved mass transfer in extending the shelf life of perishable produce, making microbubble technology a valuable tool in postharvest preservation.

Surface Cleaning and Biofilm Removal: The physical interactions of microbubbles with produce surfaces facilitate the removal of contaminants and biofilms. Biofilms are complex communities of microorganisms that adhere to surfaces, making them difficult to remove with conventional cleaning methods. Microbubbles, due to their small size and high energy, can penetrate biofilms and dislodge these microorganisms, ensuring that the produce is thoroughly cleaned. Bui, Nguyen, & Le (2022) have demonstrated the effectiveness of microbubbles in surface cleaning and biofilm removal, highlighting their potential to improve food safety and quality.

4. GENERATION OF MICROBUBBLES

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

4.1 Decompression

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

In addition to decompression, cavitation can also generate microbubbles. Cavitation occurs when the pressure in the decompression region drops to the appropriate value of the water-vapor pressure, leading to the nucleation of vapor in liquids. Cavitation bubbles may contain both water vapor and some desorbed air, but much of the vapor condenses as the pressure recovers away from the decompression region. The initial liquid saturation level influences the extent of air desorption and, therefore, the size and number of generated microbubbles. High saturation levels increase the number of nucleation events and the amount of air in the nucleated bubbles, resulting in a higher number density (on the order of 10^{10} m^{-3}) and larger average size of the microbubbles (around 10 μm) (Maeda et al., 2015; Oikonomidou et al., 2018).

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

4.2 Venturi Generator

The operation of a Venturi microbubble generator is illustrated in Figure 2. This method involves millimetric bubbles entering the converging section of a Venturi tube, driven by the low hydrodynamic pressure created by rapid liquid flow (Thang & Davis, 1979). As the bubbles pass through the diverging section, they undergo rapid deceleration and severe fragmentation, resulting in a fine dispersion carried downstream by the liquid flow (Fujiwara et al., 2007; Huang et al., 2020; Zhao et al., 2019).

Additionally, bubbles can be nucleated by hydrodynamic cavitation if the pressure at the converging section of the Venturi tube is sufficiently low (Pawar et al., 2017). In a common variant known as the ejector-type generator, bubbles are entrained into the generator by a fast liquid jet introduced through an ejector at the throat of the Venturi tube (Gourich et al., 2007; Haidl et al., 2021).

Venturi generators are highly reliable and simple to operate, with no moving parts. They can generate high bubble number density with low energy consumption. The size and number density of the generated microbubbles depend on the liquid flow rate and the generator design, particularly the opening angle of the diverging tube section (Huang et al., 2020). Higher liquid flow rates induce lower pressure at the converging section of the tube, driving more gas into the liquid and increasing the bubble number density (Sakamatapan et al., 2021). Higher flow rates also generate rapid deceleration, pressure waves, and turbulence in the diverging section, causing more severe fragmentation and leading to smaller bubbles (Sakamatapan et al., 2021). Similarly, a larger opening angle decelerates the flow more rapidly, generating finer, although less uniform, microbubble dispersions (Lee et al., 2019).

The combined influence of fluid properties, flow conditions, and tube configurations is often discussed through dimensionless, empirical correlations. For instance, the average diameter dd of the bubbles generated in the Venturi tube relative to the diameter of the Venturi throat DD scales approximately as a weak power law d/D∼Oh−0.6Re−1.1d/D \sim \text{Oh}^{-0.6} \text{Re}^{-1.1}, where Oh is the dimensionless liquid Ohnesorge number and Re is the dimensionless Reynolds number based on the diameter of the Venturi tube throat (Huang et al., 2020).

Recent advancements in understanding bubble fragmentation mechanisms (Li et al., 2019; Sakamatapan et al., 2021) and the support of realistic computational fluid dynamic models (Jensen et al., 2020; Sharma et al., 2018; Simpson & Ranade, 2019) have motivated new designs. For example, Lee et al. (2021) developed a two-dimensional Venturi generator with a non-constant opening angle in the diverging section, designed to optimize bubble breakup by improving the interaction between entrained bubbles and the more energetic central flow.

Multistage and combined generation mechanisms have also been employed to enhance generator performance. Ding et al. (2021) developed a two-stage generator, where a second Venturi tube in series intensifies the breakup mechanism, reducing bubble size to the sub micrometer scale. Wu et al. (2022) and C. Li et al. (2022) reported better generator performance by inducing high-speed swirling flow in the Venturi tube.

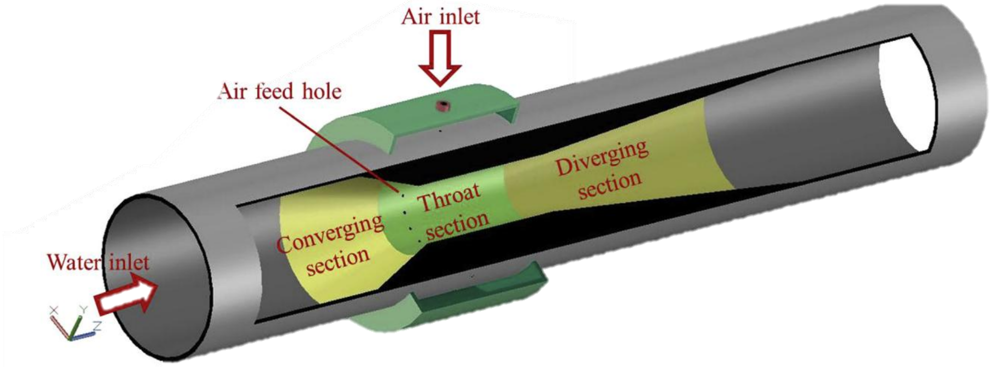

Fig 2. Venturi-type microbubble generator. (Zhao et al.,2017)

4.3 Ultrasound

Ultrasound devices generate microbubbles through the application of large-amplitude waves, also known as power ultrasound, with frequencies ranging from 20 kHz to a few hundred kilohertz (Kentish & Feng, 2014). In the food industry, power ultrasound is typically produced using acoustic transducers. These transducers utilize the inverse piezoelectric effect to convert electrical energy into acoustic oscillations, creating the necessary conditions for microbubble formation (Dion, 2011; Gogate & Pandit, 2015).

Ultrasound works by generating alternating low- and high-pressure waves in a liquid. When the ultrasound is sufficiently powerful, it can induce cavitation during the low-pressure period of the sound wave. Cavitation is the process of forming small vapor-filled cavities or bubbles within the liquid. The average bubble radius r can be roughly estimated by the simple relation r=3/F, where FF represents the ultrasound frequency (Kentish & Feng, 2014).

In addition to cavitation, ultrasound can also create microbubbles through a mechanism known as rectified diffusion. This process involves the gradual enlargement of interstitial gas pockets within the liquid. As the gas pocket pulsates, more gas enters during the expansion phase (when the surface area is larger) than exits during the compression phase (when the surface area is smaller), leading to a gradual increase in the amount of gas within the pocket (Crum, 1984; Lohse, 2018).

The response of the generated microbubbles to the pulsating field can vary significantly depending on their size, especially near their resonance frequency. When subjected to ultrasound, microbubbles can undergo inertial cavitation, where they resonate and grow to more than twice their original size during the low-pressure period. They then collapse violently during the high-pressure period due to the inertia of the surrounding liquid (Mondal et al., 2021). This collapse generates powerful shock waves, high-temperature spots, and strong hydrodynamic stresses.

These intense conditions can be highly beneficial in food processing, as they help inactivate microorganisms and remove hard fouling materials from food processing surfaces. The effectiveness of ultrasound in enhancing food safety and cleanliness has been demonstrated in various studies (Burfoot et al., 2017; Ehsani et al., 2022), showcasing its potential as a valuable tool in the food industry.

4.4 Swirl Flow

Swirl-flow generation is a well-established method for creating microbubbles through bubble breakup via liquid vortices and turbulence. In these generators, hydrodynamic shear induced by a high-speed rotating liquid causes macroscopic gas bubbles to stretch and subsequently pinch off, resulting in the formation of a cloud of microbubbles. The rotating flow is created by pumping the liquid through helical flow channels or by introducing it tangentially into a cylindrical mixing chamber.

Key operational parameters for swirl-flow generators include gas and liquid flow rates. Increasing the gas flow rate typically leads to larger microbubbles, whereas increasing the liquid flow rate results in smaller bubbles due to accelerated rotation speed and increased shear (Mawarni et al., 2022). This method enables simple design and the ability to generate fine bubbles, often at a lower cost compared to sonication and decompression methods (Kawahara et al., 2009; Li & Tsuge, 2006; Ohnari, 2000).

Researchers are continually working to improve generator designs. Recent progress has been driven by the availability of new fabrication methods, such as additive manufacturing, and the use of high-fidelity computer simulations for a better mechanistic understanding. For example, Kim et al. (2019) developed an innovative 3D-printed design that combines helical channels to induce swirling flow and a central tube in the axial direction to introduce compressed air. Large velocity gradients develop when the swirling flow and the axial flow mix in an upstream discharge nozzle, inducing strong shear and efficient bubble breakup to sizes in the 10–100 μm range.

However, this approach can be a disadvantage in applications where high bubble densityis required, as exceeding a threshold air flow rate results in enhanced coalescence, leading to larger bubbles and reduced bubble number density.

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

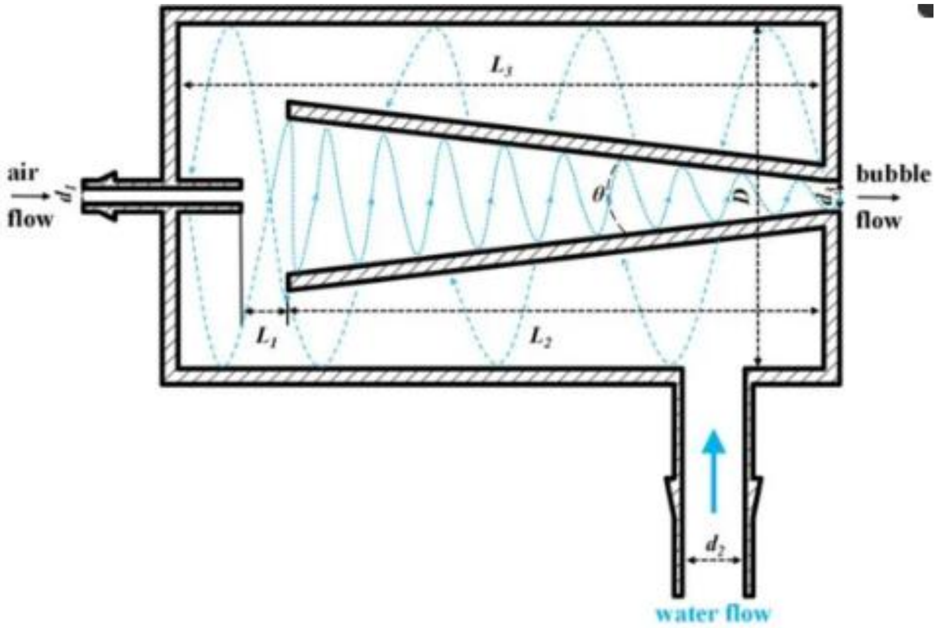

Fig 3. The sectional view of the micro-nano bubble generator.(Hu et al., 2023)

5. APPLICATIONS IN VEGETABLE AND FRUIT PRESERVATION

5.1 Microbubble-Ozone Treatment

Microbubble-ozone treatment has proven to be highly effective in reducing microbial populations and removing pesticide residues from fruits and vegetables. Studies by Nakabayashi

& Kobayashi (2021) and Takahashi et al. (2023) have demonstrated that the introduction of ozone microbubbles into washing systems can significantly enhance the safety and quality of produce. This method is particularly beneficial for delicate produce such as leafy greens, berries, and citrus fruits, where traditional cleaning methods may be less effective or too harsh. The oxidative properties of ozone combined with the high surface area of microbubbles ensure thorough decontamination without damaging the produce.

5.2 Microbubble-Carbon Dioxide Treatment

Microbubble-carbon dioxide treatment creates a modified atmosphere around the produce, which helps delay ripening and senescence. By surrounding fruits and vegetables with CO_2 microbubbles, the respiration rate of the produce is slowed, effectively extending their shelf life. Research by Agarwal, Ng, & Liu (2011) and Zhang et al. (2021) has shown that this method is particularly effective for the storage of apples, strawberries, and tomatoes. The controlled atmosphere provided by CO_2 microbubbles helps maintain the freshness and nutritional quality of the produce for longer periods, reducing food waste and ensuring better availability of fresh produce.

5.3 Microbubble-Water Washing Systems

Microbubble-water washing systems enhance the removal of dirt, microbes, and pesticide residues from the surfaces of fruits and vegetables. The small size and high energy of microbubbles allow them to penetrate and dislodge contaminants more effectively than conventional washing methods. Wu et al. (2019) have demonstrated that microbubble washing systems can achieve superior cleaning results while also reducing water consumption. This makes microbubble technology a sustainable and efficient alternative for the postharvest cleaning of produce, ensuring food safety and quality while conserving valuable water resources.

5.4 Microbubble-Hypochlorous Acid Disinfection

The use of microbubbles in conjunction with hypochlorous acid enhances antimicrobial efficiency with lower concentrations of chemicals. This combination ensures effective disinfection while minimizing the chemical load on the produce. Studies by Bui, Nguyen, & Le

(2022) and Zhang et al. (2021) have shown that microbubble-hypochlorous acid treatment is particularly effective for the sanitization of fresh-cut vegetables and minimally processed fruits. The physical action of microbubbles improves the distribution and contact of hypochlorous acid with microbial contaminants, resulting in more efficient and thorough disinfection.

6. EFFECTIVENESS AND BENEFITS OF MICROBUBBLE PRESERVATION

Extended Shelf Life: One of the most significant benefits of microbubble technology is its ability to extend the shelf life of fruits and vegetables. By slowing down enzymatic degradation and microbial spoilage, microbubbles help keep produce fresh for longer periods. Studies by Nakabayashi & Kobayashi (2021) and Takahashi et al. (2023) have shown that microbubble treatments can effectively inhibit the growth of spoilage microorganisms, reducing the rate at which produce deteriorates. This extended shelf life not only benefits consumers by providing fresher produce but also helps reduce food waste and economic losses for producers and retailers.

Retention of Nutritional Quality: Microbubble technology also plays a crucial role in preserving the nutritional quality of fruits and vegetables. Traditional preservation methods can often result in the loss of essential vitamins and antioxidants. However, microbubble treatments minimize these losses, ensuring that the produce retains its nutritional value. Research by Wu et al. (2019) and Zhang et al. (2021) has demonstrated that microbubble treatments can effectively preserve the nutritional quality of produce, maintaining higher levels of vitamins and antioxidants compared to conventional methods. This ensures that consumers receive produce that is not only fresh but also nutritionally rich.

Eco-Friendly and Reduced Chemical Usage: Microbubble technology offers an eco-friendly alternative to traditional preservation methods, which often rely on chlorine-based disinfectants and synthetic preservatives. By decreasing the reliance on these chemicals, microbubble treatments contribute to a more sustainable and environmentally friendly approach to food preservation. Agarwal, Ng, & Liu (2011) have highlighted the potential of microbubble technology to reduce chemical usage, making it a safer option for both consumers and the environment. The reduced need for synthetic preservatives also means that produce can be treated more naturally, appealing to health-conscious consumers who prefer minimal chemical intervention.

Improved Food Safety: Microbubble technology enhances food safety by effectively inactivating harmful microorganisms without compromising the quality of the produce. The high surface area and unique physicochemical properties of microbubbles allow for efficient microbial inactivation, ensuring that fruits and vegetables are safe for consumption. Tsuge (2015) and Takahashi et al. (2023) have documented the ability of microbubble treatments to enhance microbial inactivation, providing an additional layer of safety for consumers. This improved food safety is particularly important in reducing the risk of foodborne illnesses and ensuring the overall quality of the produce.

7. CHALLENGES AND FUTURE PERSPECTIVES

While microbubble technology offers numerous benefits for the preservation of fruits and vegetables, its widespread adoption faces several hurdles:

Scalability and Cost: One of the primary challenges is the high initial investment required for microbubble generation systems. These advanced systems can be expensive to implement, especially for small-scale producers. Nakabayashi & Kobayashi (2021) and Zhang et al. (2021) have noted that the cost-effectiveness of these systems needs to be improved to make them more accessible. Developing more affordable and scalable microbubble generation techniques will be essential for broader adoption.

Process Optimization: Another challenge lies in the need for standardized protocols tailored to different types of produce. Fruits and vegetables vary widely in their properties, and a one-size-fits-all approach may not be effective. Wu et al. (2019) and Takahashi et al. (2023) emphasize the importance of optimizing microbubble treatments for specific produce types to ensure maximum efficacy. This involves fine-tuning variables such as bubble size, concentration, and exposure time.

Consumer Acceptance: The success of any new technology also depends on consumer acceptance. People can be wary of novel preservation techniques, particularly when it comes to food safety and quality. Educating consumers about the benefits and safety of microbubble technology will be crucial in overcoming skepticism. Bui, Nguyen, & Le (2022) suggest that transparent communication and demonstrating the tangible benefits of this technology can help build consumer trust.

Regulatory Approvals: Compliance with food safety and environmental regulations is another significant challenge. Microbubble technology must meet stringent regulatory standards to ensure it is safe for use in food preservation. Agarwal, Ng, & Liu (2011) highlight the need for comprehensive regulatory approvals to facilitate the adoption of this technology. Navigating the regulatory landscape and obtaining necessary certifications can be time-consuming and costly.

Future Research Directions: To address these challenges, future research should focus on optimizing microbubble formulations and integrating them with other preservation methods, such as cold storage and edible coatings. Combining microbubble technology with existing preservation techniques can enhance its effectiveness and provide a multi-faceted approach to extending shelf life. Additionally, long-term studies assessing the safety and sustainability of microbubble treatments are essential to ensure they are viable for widespread use (Tsuge, 2015; Zhang et al., 2021).

8. CONCLUSION

Microbubble technology stands out as a sustainable and effective alternative for the preservation of vegetables and fruits. Its unique ability to enhance microbial safety, extend shelf life, and maintain the nutritional and sensory quality of produce makes it a promising innovation in the food industry. By leveraging the distinctive properties of microbubbles, this technology addresses the limitations of traditional preservation methods, offering a more eco-friendly and efficient solution.

The journey toward widespread adoption, however, is not without its challenges. High initial investment costs, the need for process optimization, consumer acceptance, and regulatory approvals are hurdles that need to be overcome. Nevertheless, the potential benefits of microbubble technology make it a worthwhile pursuit.

Further research and technological advancements will be crucial for its successful commercial implementation. Optimizing microbubble formulations, integrating this technology with other preservation methods, and conducting long-term studies to assess safety and sustainability are essential steps forward. As the food industry continues to evolve, microbubble technology holds the promise of transforming the way we preserve fruits and vegetables, ensuring they remain fresh, safe, and nutritious for consumers worldwide (Nakabayashi & Kobayashi, 2021; Takahashi et al., 2023).

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