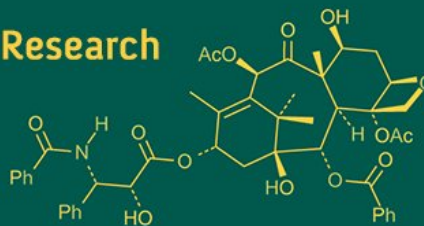


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(9): 773-781
www.biochemjournal.com
Received: 16-07-2025
Accepted: 19-08-2025

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Application of nanobubbles in post-harvest management: A comprehensive review

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DOI: <https://www.doi.org/10.33545/26174693.2025.v9.i9Sj.5593>

Abstract

Nanobubbles, defined as gas-filled cavities less than 200 nm in diameter, have emerged as a novel technology in agriculture and food science. Their unique physicochemical properties, such as high surface charge, long residence time in liquids, and ability to generate reactive oxygen species, make them promising for post-harvest management. This review synthesizes recent advances in the application of nanobubbles across the post-harvest chain, including washing, disinfection, preservation, and quality enhancement of fruits, vegetables, and grains. The paper discusses mechanisms of microbial inactivation, ethylene degradation, and enhanced oxygenation, which contribute to extending shelf life and reducing losses. Case studies highlight the effectiveness of nanobubble treatments in reducing spoilage organisms and pesticide residues while maintaining nutritional and sensory quality. Challenges related to scalability, standardization, and regulatory approval are also addressed. The review concludes with future directions, focusing on integrating nanobubbles with cold storage, smart packaging, and sustainable food systems.

Keywords: Nanobubbles, post-harvest management, shelf life extension, microbial inactivation, food preservation

Introduction

Post-harvest management remains a critical factor in ensuring food security, reducing waste, and improving the economic returns of agricultural production ^[1, 2]. Globally, an estimated 30 to 40 percent of fruits and vegetables are lost or wasted after harvest due to microbial spoilage, physiological deterioration, and improper handling during storage and distribution. ^[2, 3] The Food and Agriculture Organization (FAO) estimates that these post-harvest losses account for nearly 1.3 billion tons of food every year, representing both an economic burden and a major challenge to sustainability ^[1, 3]. In low- and middle-income countries, losses are more severe, often exceeding 40 percent for perishable crops such as leafy greens, berries, and tomatoes. This persistent problem has prompted the search for novel technologies that can improve preservation, enhance food safety, and extend shelf life without compromising nutritional and sensory quality ^[4, 5].

Nanotechnology has gained significant attention in agriculture and food sciences in recent years ^[6, 7]. Among the emerging approaches, nanobubbles, also known as ultrafine bubbles, represent a promising innovation. These bubbles are defined as gas-filled cavities smaller than 200 nanometers in diameter. Unlike conventional microbubbles, nanobubbles exhibit unique physical and chemical properties, including high stability in aqueous systems, a large surface-to-volume ratio, high zeta potential, and the ability to generate reactive oxygen species. Their long residence time in liquids and capability to modify water chemistry make them particularly attractive for applications in food preservation and safety ^[8, 9].

The role of nanobubbles in post-harvest management is increasingly being investigated. Several studies have demonstrated that oxygen and ozone nanobubbles can enhance the oxidative stress on microbial contaminants, leading to effective disinfection of fresh produce surfaces ^[10, 11]. For example, ozone nanobubbles have been reported to inactivate foodborne pathogens such as *Escherichia coli* and *Salmonella* at lower concentrations compared to traditional sanitizers, thereby reducing chemical usage while maintaining safety standards. Beyond disinfection, nanobubbles improve oxygen solubility in water, which can

influence respiration rates in harvested fruits and vegetables, potentially slowing down senescence processes. Furthermore, their ability to degrade ethylene, a ripening hormone, suggests a role in extending storage life for climacteric fruits such as bananas, mangoes, and avocados^[4, 7].

Traditional post-harvest preservation methods, including chlorination, cold storage, and modified atmosphere packaging, continue to play an essential role in reducing losses. However, they also present limitations such as chemical residues, environmental concerns, and high energy consumption^[9, 10]. Nanobubbles offer a sustainable alternative by minimizing chemical inputs, lowering microbial risks, and potentially reducing dependence on energy-intensive technologies. As global attention shifts toward greener and more sustainable food supply chains, nanobubbles are gaining recognition as a technology with both scientific and commercial potential^[10, 11].

This review aims to provide a comprehensive synthesis of the current knowledge on nanobubbles and their application in post-harvest management^[11, 12]. It will explore their physicochemical properties, mechanisms of action, and practical applications in the washing, disinfection, preservation, and storage of fruits, vegetables, and grains. Comparative analyses with conventional methods, challenges in large-scale adoption, and opportunities for integration with emerging technologies will also be discussed. The goal is to highlight the potential of nanobubbles to contribute to sustainable post-harvest practices and stimulate further research and development in this promising field^[13, 14].

Fundamentals of Nanobubbles

Nanobubbles, often referred to as ultrafine bubbles, are defined as gas-filled cavities with diameters less than 200 nanometers. This size distinction is crucial, as it differentiates them from microbubbles, which typically measure between 1 and 100 micrometers^[11, 12]. The nanoscale dimension gives nanobubbles unique physical and chemical properties not observed in larger bubbles, making them highly stable and functionally versatile in liquid environments. Their ability to persist in water for weeks or even months, rather than collapsing within seconds like microbubbles, has been the subject of increasing scientific interest^[7, 10].

One of the most striking features of nanobubbles is their high surface-to-volume ratio. This characteristic enhances interfacial interactions between the gas core and the surrounding liquid, thereby increasing their reactivity and functional efficiency. Another defining property is their high zeta potential, which imparts a strong surface charge that stabilizes the nanobubbles against coalescence^[14, 15]. As a result, nanobubbles maintain long-term stability in aqueous systems, making them suitable for continuous applications in agricultural and food systems where extended activity is necessary^[12, 13].

Nanobubbles are also capable of generating reactive oxygen species (ROS) during their collapse or through surface interactions^[16, 17]. These species, including hydroxyl radicals and singlet oxygen, play a critical role in antimicrobial action by damaging microbial membranes, nucleic acids, and proteins. Ozone nanobubbles, in particular, exhibit strong oxidative capacity and have been widely studied for their potential to replace conventional

chemical disinfectants in water and food processing. Oxygen nanobubbles, on the other hand, can enhance oxygen solubility in water, creating microenvironments that support oxidative processes and influence metabolic activities in biological systems^[18, 20].

The production of nanobubbles has been achieved through several methods, each with its advantages and limitations^[21, 22]. Common techniques include hydrodynamic cavitation, where high-pressure liquid is forced through an orifice to generate bubbles; acoustic cavitation, which uses ultrasound waves to form and collapse bubbles; and electrochemical methods, where gas is generated directly in water through electrolysis^[23, 24]. Advances in nanobubble generators have improved efficiency, allowing for scalable production that is necessary for industrial and agricultural applications^[24, 25].

Different types of nanobubbles can be generated depending on the gas used. Oxygen nanobubbles are widely employed for their ability to increase dissolved oxygen content, which is beneficial in reducing anaerobic microbial growth^[7, 23]. Ozone nanobubbles are valued for their disinfection capacity, as they combine the strong oxidative power of ozone with the stability and controlled release properties of nanobubbles. Carbon dioxide nanobubbles have been investigated for their role in pH regulation and inhibition of microbial growth, while nitrogen nanobubbles may be used in applications where oxygen removal or inert environments are required^[1, 7].

These physicochemical properties collectively underpin the diverse applications of nanobubbles in post-harvest management. Their stability ensures prolonged functionality during washing and storage processes^[17, 18]. Their ability to modulate water chemistry provides opportunities for improving produce safety and quality. By combining chemical efficiency with physical stability, nanobubbles emerge as a multifunctional tool that aligns with current demands for sustainable and residue-free technologies in food systems^[19, 20].

Mechanisms Relevant to Post-Harvest Applications

The effectiveness of nanobubbles in post-harvest management depends on a combination of physical and chemical mechanisms^[21, 25]. Their nanoscale properties allow them to interact uniquely with biological surfaces, water chemistry, and gaseous environments. Understanding these mechanisms is essential for assessing their role in food preservation and safety^[25, 26].

A primary mechanism is the enhancement of dissolved oxygen content in water. Oxygen nanobubbles significantly increase oxygen solubility due to their stability and slow-release properties. Higher oxygen availability creates an unfavourable environment for anaerobic microorganisms, which are often responsible for spoilage and off-flavour development in stored produce. Enhanced oxygenation can also reduce fermentation processes and limit the growth of pathogens such as *Clostridium* species that thrive under low-oxygen conditions^[27, 28].

Nanobubbles also generate reactive oxygen species (ROS) during collapse or surface reactions^[21, 22]. Hydroxyl radicals, in particular, have strong oxidative capacity, capable of damaging microbial membranes, proteins, and nucleic acids. This oxidative stress leads to microbial inactivation without leaving harmful chemical residues^[12, 16]. Ozone nanobubbles are especially effective, as ozone itself is a powerful oxidant. Studies have shown that ozone

nanobubbles inactivate *Escherichia coli* and *Salmonella* on fresh produce surfaces at lower doses compared to free ozone, thereby improving food safety while minimizing oxidative damage to plant tissues^[7, 12].

Another important mechanism involves the role of nanobubbles in degrading ethylene, the plant hormone responsible for fruit ripening and senescence. Ethylene accelerates physiological changes such as softening, color development, and loss of firmness in climacteric fruits^[29, 30]. Nanobubbles, especially those containing ozone, react with ethylene molecules, lowering their concentration in the storage environment. By reducing ethylene accumulation, nanobubbles help delay ripening and extend the shelf life of sensitive crops such as bananas, mangoes, and avocados^[31, 32].

The physical properties of nanobubbles also contribute to their post-harvest applications. Their negatively charged surfaces allow them to attach to microbial cell membranes, enhancing local oxidative stress and promoting physical disruption of microbial cells^[17, 19]. The collapse of nanobubbles near surfaces creates localized energy release, which can dislodge contaminants and biofilms from produce surfaces. This cleaning effect has been reported in leafy greens and tomatoes, where nanobubble treatment reduced microbial load and pesticide residues more effectively than conventional washing methods^[7, 12].

Furthermore, nanobubbles influence water chemistry by modifying pH and oxidation-reduction potential (ORP). Ozone nanobubbles, for instance, increase ORP, creating an oxidative environment that is hostile to microbial survival^[20, 21]. Carbon dioxide nanobubbles, on the other hand, lower pH, which can further inhibit microbial growth. These chemical changes enhance the sanitizing effect of nanobubble treatments without the need for high concentrations of chemical disinfectants^[22, 23].

Collectively, these mechanisms provide a multifaceted approach to post-harvest management^[24, 25]. By increasing oxygen availability, generating ROS, degrading ethylene, disrupting biofilms, and modifying water chemistry, nanobubbles can simultaneously enhance microbial safety, maintain quality, and extend shelf life. This makes them a versatile tool that addresses both safety and sustainability challenges in modern food supply chains^[26, 27].

Application in Post-Harvest Washing and Disinfection

Washing and disinfection are critical steps in post-harvest handling of fruits and vegetables. These processes aim to remove soil, pesticide residues, and microbial contaminants that can compromise food safety and accelerate spoilage^[28, 31]. Conventional washing methods, which rely on chlorinated water or chemical sanitizers, have well-documented limitations. Chlorine, though widely used, is associated with the formation of harmful by-products such as trihalomethanes and chloramines, reduced effectiveness in the presence of organic matter, and growing consumer concerns about chemical residues. In this context, nanobubbles, particularly ozone and oxygen nanobubbles, have gained attention as a sustainable alternative for fresh produce sanitation^[32, 33].

Ozone nanobubbles have shown strong antimicrobial activity against a broad range of foodborne pathogens and spoilage organisms^[33, 34]. Their nanoscale size allows them to penetrate microscopic crevices on produce surfaces where microbes often hide. Upon collapse or reaction, they release

reactive oxygen species that oxidize microbial cell components, leading to inactivation^[37, 38]. Studies have demonstrated that washing lettuce, spinach, and strawberries with ozone nanobubble water reduced populations of *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* by several log cycles. These reductions are comparable to or greater than those achieved with chlorine-based treatments, but without leaving chemical residues^[35, 36].

In addition to pathogen inactivation, nanobubbles improve the removal of pesticide residues from fruit and vegetable surfaces^[37, 38]. The physical action of bubble collapse generates microstreaming and shear forces, which help detach residues that adhere strongly to plant cuticles. Ozone further contributes by oxidizing pesticide molecules into less harmful compounds. For example, treatments with ozone nanobubbles have been reported to degrade organophosphates and carbamates on cucumber and tomato surfaces, making them safer for consumption and reducing chemical load in food supply chains^[38, 39].

Leafy greens, which are particularly prone to microbial contamination due to their large surface area and porous structure, have been a focus of nanobubble research^[39, 40]. Washing with ozone nanobubbles not only reduced microbial loads but also preserved leaf texture and colour better than chlorine washes. Similarly, in tomatoes and peppers, nanobubble treatments maintained surface gloss and reduced spoilage during storage. These findings indicate that nanobubbles provide both microbiological safety and quality retention advantages^[21, 28].

An additional advantage of nanobubbles lies in their long-term stability. Unlike conventional ozone treatments, where ozone gas quickly dissipates in water, ozone nanobubbles maintain effective concentrations for extended periods^[23, 27]. This prolonged activity ensures that washing water retains its sanitizing power over multiple uses, reducing water consumption and enhancing operational efficiency in commercial packinghouses^[29, 31].

Comparative evaluations have highlighted the cost-effectiveness of nanobubble technology^[41, 42]. Although initial investment in nanobubble generators may be higher than standard chlorination systems, the reduced need for chemical inputs, longer shelf life of wash water, and enhanced consumer acceptance make the approach economically viable in the long term. Furthermore, regulatory agencies in several countries are beginning to acknowledge ozone-based nanobubble technologies as safe and effective interventions for fresh produce sanitation, which is likely to accelerate adoption^[43, 44].

Role in Shelf Life Extension

Extending the shelf life of fresh produce is a central goal in post-harvest management^[42, 43]. Fruits and vegetables are highly perishable due to their high-water activity, metabolic activity, and susceptibility to microbial spoilage. Conventional methods such as refrigeration, controlled atmosphere storage, and chemical preservatives have been used widely, but each has limitations related to cost, chemical residues, or limited efficacy. Nanobubbles, with their combined physical and chemical effects, present a promising alternative for extending shelf life while maintaining quality^[44, 45].

One of the primary mechanisms by which nanobubbles extend shelf life is through microbial control. Spoilage

organisms such as molds, yeasts, and bacteria are major contributors to post-harvest losses [46, 47]. Nanobubbles, particularly those containing ozone or oxygen, generate reactive oxygen species that disrupt microbial membranes and inhibit enzymatic activity. Studies have shown that strawberries treated with ozone nanobubbles exhibited a significant reduction in *Botrytis cinerea*, a common gray mold pathogen, resulting in a delay of visible spoilage by several days compared to untreated controls. Similarly, lettuce washed with ozone nanobubbles retained a lower microbial load during storage, slowing deterioration and reducing waste [48, 49].

Nanobubbles also influence physiological processes in fruits and vegetables [42, 43]. Ethylene is a critical plant hormone that accelerates ripening and senescence in climacteric fruits such as bananas, avocados, and tomatoes. Ozone nanobubbles degrade ethylene molecules, thereby lowering the hormone concentration in the storage environment. This slows down ripening and softening, extending storage life without altering sensory attributes. For example, bananas treated with ozone nanobubbles maintained firmness and bright yellow coloration longer than untreated fruits, allowing for extended marketability [44, 45].

Respiration rate is another important factor affecting post-harvest life. Elevated respiration accelerates the depletion of stored sugars and nutrients, leading to softening, wilting, and nutrient loss [22, 34]. Oxygen nanobubbles increase dissolved oxygen levels in washing or storage water, which can help maintain oxidative balance and stabilize respiration in certain crops. Leafy greens stored in oxygen nanobubble water showed delayed wilting and retained chlorophyll content for longer periods compared to conventional water treatments [1, 4].

Quality attributes such as color, texture, and nutritional value are also preserved by nanobubble treatment [4]. Tomato fruits washed with ozone nanobubbles retained higher firmness and lower microbial load after two weeks of storage compared to chlorine-washed tomatoes. Nutritional qualities, including vitamin C and antioxidant activity, were better preserved in strawberries treated with ozone nanobubbles, suggesting that nanobubbles minimize oxidative damage to sensitive bioactive compounds while still providing antimicrobial action [7, 11].

Beyond fruits and vegetables, grains and legumes can also benefit indirectly from nanobubble applications. High microbial loads in moist environments accelerate mold growth and mycotoxin production [11, 12]. Preliminary studies suggest that washing or storing grains with nanobubble-treated water reduces surface microbial populations and lowers the risk of toxin contamination, thereby extending safe storage life [12, 13].

Collectively, these results highlight the multifunctional role of nanobubbles in shelf life extension [14, 15]. They slow microbial growth, delay physiological deterioration, reduce ethylene accumulation, and help maintain sensory and nutritional qualities. Importantly, these effects are achieved without the addition of chemical preservatives, aligning with consumer demand for natural and residue-free preservation methods [16, 17].

Nanobubbles in Grain and Cereal Preservation

Grains and cereals form the foundation of food security worldwide, yet they are highly vulnerable to deterioration during storage [11, 12]. Post-harvest losses in cereals occur primarily due to microbial contamination, insect infestation,

and the development of mycotoxins under unfavourable storage conditions. Traditional preservation methods, including drying, fumigation, and chemical treatments, reduce these risks but face challenges related to sustainability, chemical residues, and environmental impact. Nanobubble technology offers a novel approach to grain preservation by improving microbial control, enhancing moisture management, and reducing toxin development [13, 16].

Moisture is a key factor influencing grain stability. High moisture content accelerates fungal growth and creates conditions conducive to aflatoxin and ochratoxin production by *Aspergillus* and *Penicillium* species [11, 12]. Nanobubbles, particularly ozone nanobubbles, have been shown to improve drying efficiency when applied as part of washing or pre-storage treatments. Their physical action helps detach surface contaminants and reduces microbial load, while the oxidative effect of ozone nanobubbles suppresses mold spores. Grains washed with ozone nanobubble water exhibited lower initial microbial counts and slower microbial resurgence during storage compared to grains washed with untreated water [17, 18].

Microbial inactivation is another important benefit. Ozone nanobubbles penetrate micro-cracks and crevices in grain kernels where conventional washing often fails to reach [21, 22]. The release of reactive oxygen species damages microbial membranes and prevents colonization. Studies on rice and wheat have demonstrated that nanobubble treatments significantly reduced surface-borne bacteria and fungi, prolonging storage life without the use of synthetic fungicides [11, 12]. This residue-free approach addresses growing consumer and regulatory concerns regarding chemical safety in staple foods [19, 20].

Nanobubbles also show potential in reducing mycotoxin risks. Mycotoxins such as aflatoxin B1 and deoxynivalenol are stable compounds that pose severe health risks [15, 16]. While direct degradation of these toxins by nanobubbles is still under investigation, evidence suggests that ozone nanobubbles can oxidize toxin precursors and suppress the growth of mycotoxin-producing fungi [19, 20]. In maize treated with ozone nanobubbles, the incidence of *Aspergillus flavus* contamination was markedly lower, leading to reduced aflatoxin levels during storage. This approach could play a vital role in improving food safety in regions where mycotoxin contamination is a persistent challenge [17, 18].

Integration of nanobubbles with milling and processing has also been explored. Pre-treatment of rice with nanobubble water prior to milling improved kernel whiteness, reduced microbial load, and enhanced storage stability of milled rice [23, 24]. This suggests that nanobubbles not only benefit raw storage but also contribute to maintaining quality in processed grains [21, 22].

While the research is still at an early stage compared to fruits and vegetables, the potential of nanobubbles in grain and cereal preservation is clear [21, 22]. They provide an environmentally friendly, residue-free method to reduce microbial contamination, lower toxin risks, and enhance the stability of stored grains. With further optimization and scale-up, nanobubble technology could become an important tool for improving grain safety and reducing losses in global supply chains [25, 26].

Integration with Cold Storage and Packaging

Cold storage and packaging are two of the most widely adopted strategies in post-harvest management. Refrigeration slows metabolic activity and microbial growth, while packaging systems such as modified atmosphere packaging (MAP) and vacuum sealing regulate gas composition and moisture exchange^[11, 12]. Although these methods are effective, their limitations include high energy consumption, material waste, and reduced effectiveness against certain microbial contaminants. The integration of nanobubbles with cold storage and packaging has emerged as a promising approach to overcome these challenges and improve the preservation of fresh produce^[43, 44].

In cold storage systems, nanobubbles enhance microbial safety by maintaining oxidative balance in storage water and air circulation systems. For instance, ozone nanobubbles can be introduced into wash water before storage or directly into humidification systems used in refrigerated chambers^[45, 46]. This integration reduces microbial populations on stored fruits and vegetables while maintaining high humidity, which is essential for preventing desiccation. Experiments with strawberries and grapes showed that nanobubble pre-treatment before cold storage delayed microbial spoilage by up to one week compared to conventional washing. This synergistic effect arises from the combined action of low temperature, which slows microbial growth, and oxidative disinfection, which reduces initial microbial loads^[47, 48].

Packaging technologies can also benefit from nanobubble applications^[49, 50]. Pre-washing with ozone nanobubbles before packaging reduces the microbial load and pesticide residues, lowering the risk of spoilage inside sealed packs. Moreover, nanobubble treatment can modify the internal environment of packaging by reducing ethylene levels and slowing down respiration rates^[50, 51]. For climacteric fruits like tomatoes and bananas, nanobubble pre-treatment has been linked to delayed ripening and prolonged marketability when stored under MAP conditions. Leafy greens packaged after nanobubble treatment retained freshness and crispness longer than those subjected to chlorine washes^[52, 53].

Another advantage is sustainability. Integrating nanobubbles reduces the reliance on high doses of chemical sanitizers, decreasing chemical residues in both food and wash water^[54, 55]. This reduces environmental impact and aligns with the growing demand for clean-label and eco-friendly preservation practices. Furthermore, because ozone nanobubbles are generated on-site and decompose naturally into oxygen, they eliminate the need for transporting or handling hazardous chemicals, which improves worker safety and lowers operational risks^[56, 57].

Energy efficiency is another important consideration.^(56,58) Although cold storage remains energy-intensive, the use of nanobubbles can reduce the required storage time by slowing deterioration at earlier stages. Shorter storage cycles translate to lower refrigeration demand, contributing to energy savings in supply chains. In developing countries, where cold chain infrastructure is often limited, combining moderate refrigeration with nanobubble treatment could provide a cost-effective solution to minimize losses^[59, 60].

Taken together, the integration of nanobubbles with cold storage and packaging offers a multi-layered approach to preservation^[61, 62]. Nanobubbles reduce initial contamination, modify ethylene and respiration dynamics, and enhance microbial safety, while storage and packaging

provide controlled environments for prolonged shelf life. This complementary relationship strengthens the potential of nanobubbles to be adopted as part of modern post-harvest systems, particularly in supply chains that prioritize sustainability and food safety^[63, 64].

Comparative Analysis with Conventional Methods

The effectiveness of nanobubbles in post-harvest management must be considered in the context of existing preservation and sanitation methods^[52, 53]. Conventional technologies such as chlorination, ultraviolet (UV) irradiation, and ozone fumigation have been widely adopted in the fresh produce and grain sectors^[52, 53]. While these methods have contributed significantly to reducing microbial contamination and extending shelf life, they also present limitations related to chemical residues, environmental impact, cost, and consumer acceptance. Nanobubbles, with their unique physicochemical properties, offer several advantages that can complement or even replace traditional methods in certain applications^[61, 64].

Chlorination is the most common disinfection strategy in post-harvest washing. It is cost-effective and widely available, but its efficacy decreases in the presence of organic matter, which rapidly consumes free chlorine^[65, 66]. Additionally, chlorine treatment generates harmful by-products such as trihalomethanes, which pose potential health risks. Consumer concerns about chemical residues have also led to reduced acceptance of chlorine-based methods in some markets. In contrast, ozone nanobubbles achieve equivalent or greater microbial inactivation without leaving toxic residues. Ozone decomposes into oxygen after use, making it environmentally safer while providing strong antimicrobial action^[67, 68].

UV irradiation is another method used to inactivate microbes on produce surfaces. While UV light can reduce microbial loads effectively, its penetration is limited to exposed surfaces^[59, 60]. Irregular produce surfaces, such as leafy greens or strawberries, reduce UV effectiveness because shaded areas remain untreated. Nanobubbles, due to their nanoscale size, can penetrate micro-crevices and biofilms, ensuring a more uniform antimicrobial effect. Furthermore, nanobubbles continue to provide disinfection for extended periods due to their stability in water, unlike UV, which has no residual activity once exposure ends^[61, 62].

Ozone fumigation is used in cold storage facilities to suppress microbial growth and control ethylene^[61, 62]. However, gaseous ozone has a short half-life and requires continuous generation at relatively high concentrations to remain effective^[63, 65]. This can be costly and pose occupational hazards for workers. Ozone nanobubbles overcome these limitations by providing a stable and controlled release of ozone into wash water or storage environments. Their prolonged presence reduces the need for continuous high-dose generation and improves safety by avoiding excessive ozone concentrations in the air^[67, 68].

From an economic standpoint, nanobubbles involve higher initial investment in generation equipment compared to conventional chlorination or UV systems. However, long-term operational costs may be lower due to reduced chemical inputs, extended activity of treated water, and savings from lower spoilage rates. For example, packhouses using nanobubble systems have reported that wash water could be reused for longer periods without losing

disinfecting power, thereby reducing water consumption and wastewater treatment costs^[69, 70].

In terms of sustainability, nanobubbles provide a clear advantage^[61]. They reduce reliance on synthetic chemicals, minimize water usage, and lower the carbon footprint associated with conventional preservation methods^[52, 61]. Their residue-free action aligns with consumer demand for natural and safe preservation strategies, improving marketability of produce. Regulatory trends are also shifting toward limiting chlorine residues and promoting eco-friendly alternatives, which positions nanobubbles as a competitive technology for the future^[21, 25].

Overall, while conventional methods continue to play a critical role in post-harvest management, nanobubbles offer an innovative alternative that addresses many of their shortcomings. Their superior penetration, long-lasting activity, and eco-friendly profile make them an attractive candidate for replacing or complementing traditional approaches in diverse food systems^[22, 23].

Challenges and Limitations

Despite the promising applications of nanobubbles in post-harvest management, several challenges and limitations must be addressed before widespread adoption can be achieved. These challenges span technical, economic, regulatory, and scientific dimensions^[34, 46].

A primary limitation is the lack of standardization in nanobubble generation and characterization. Different generation methods, including hydrodynamic cavitation, electrolysis, and acoustic cavitation, produce nanobubbles with varying sizes, stability, and concentrations^[12, 13]. The absence of universally accepted standards for measuring nanobubble properties complicates comparisons across studies and hinders industrial adoption. Reliable characterization methods such as nanoparticle tracking analysis and dynamic light scattering are available, but differences in measurement protocols often lead to inconsistent results. Establishing standardized guidelines for nanobubble production and evaluation is essential for ensuring reproducibility and regulatory approval^[42, 43].

Scalability is another important concern. While laboratory studies have consistently shown the effectiveness of nanobubbles in microbial inactivation, ethylene degradation, and shelf life extension, scaling the technology to commercial levels remains a challenge. Large-scale treatment of wash water or storage facilities requires robust generators capable of producing high volumes of nanobubbles consistently^[45, 46]. Current equipment can be costly, and operational optimization for different commodities is still limited. For example, fruits with waxy cuticles may require longer exposure or higher concentrations compared to leafy greens, raising questions about cost-effectiveness in diverse contexts^[47, 48].

Economic considerations also play a role. The initial investment in nanobubble generation systems is higher than that for conventional washing and disinfection systems. Although operational costs may decrease over time due to lower chemical use and water reuse, small- and medium-scale producers may struggle with the upfront costs. Cost-benefit analyses that incorporate reduced spoilage losses, enhanced market value, and consumer acceptance are needed to demonstrate long-term economic viability^[49, 50].

From a regulatory perspective, the adoption of nanobubbles faces uncertainty. While ozone and oxygen have been

approved for use in food processing by regulatory authorities in several countries, their application in nanobubble form is still under review in many regions^[41, 54]. Regulatory agencies require clear evidence of safety, efficacy, and residue-free action before granting approvals. Additionally, risk assessments regarding occupational exposure to nanobubbles or associated reactive oxygen species need to be clarified. Without regulatory harmonization, commercialization of nanobubble technology may be restricted to a few regions or applications^[62, 63].

Scientific knowledge gaps also remain. Although the antimicrobial effects of nanobubbles are well-documented, the exact molecular mechanisms underlying their stability and activity are still debated. Some studies suggest that nanobubbles generate reactive oxygen species continuously during their lifetime, while others argue that ROS are produced mainly upon collapse^[21, 22]. Similarly, the role of surface charge and cavitation energy in microbial inactivation is not fully understood. Addressing these uncertainties will require interdisciplinary research combining nanotechnology, microbiology, and food science^[17, 19].

Finally, potential unintended effects must be considered^[20, 21]. Excessive use of oxidative nanobubbles, particularly ozone, may lead to oxidative damage to plant tissues, affecting color, texture, or nutrient content. Although most studies report minimal negative impacts at optimized concentrations, careful dose-response evaluations are essential for ensuring product quality. Additionally, variations in commodity type, surface structure, and storage conditions mean that nanobubble treatments must be tailored rather than applied universally^[33, 34].

Future Directions

The application of nanobubbles in post-harvest management is still in its early stages, and several opportunities exist to expand research, optimize applications, and move toward large-scale commercialization^[23, 24]. Future directions should focus on integration with existing technologies, exploration of new uses, addressing current limitations, and aligning development with sustainability goals^[26, 27].

One important area is the integration of nanobubbles with cold storage, modified atmosphere packaging, and smart storage systems^[28, 29]. Combining nanobubble pre-treatment with refrigeration has already demonstrated synergistic effects in reducing microbial growth and extending shelf life. Future studies should evaluate how nanobubbles interact with controlled atmosphere storage, particularly for high-value crops such as berries, grapes, and tropical fruits. Incorporating nanobubbles into smart storage systems equipped with sensors and Internet of Things (IoT) platforms could allow real-time monitoring of ethylene levels, microbial load, and storage conditions, creating adaptive systems that respond dynamically to changes in produce physiology^[31, 32].

Another promising direction lies in combining nanobubbles with other novel technologies. Plasma-activated water, ultrasound, and UV-C light have all shown potential in food preservation^[19, 20]. When paired with nanobubbles, these approaches may provide additive or synergistic effects, enhancing microbial inactivation while maintaining product quality. For example, ultrasound-assisted nanobubble treatments could improve penetration into fruit cuticles and

biofilms, while plasma and nanobubbles may complement each other in oxidative degradation of pesticides and toxins [21, 22].

Research on nanobubble use in grains and cereals is still limited compared to fruits and vegetables. Future work should explore large-scale grain storage applications, focusing on microbial suppression, mycotoxin control, and moisture management. Pilot studies in silos and warehouses could provide practical insights into operational feasibility and cost-effectiveness. Extending this research to pulses and oilseeds may also help reduce losses in staple crops that are vital to global food security [23, 24].

Sustainability will be a key driver of adoption. Nanobubbles align with global efforts to reduce chemical use, minimize water consumption, and lower post-harvest losses [27, 29]. Further research should quantify the environmental benefits of nanobubble systems compared to conventional methods, including life cycle assessments of energy use, carbon emissions, and water savings. Demonstrating that nanobubbles reduce reliance on synthetic sanitizers and lower greenhouse gas emissions from refrigeration could support their promotion in policy frameworks for sustainable food systems [30, 32].

Regulatory acceptance and consumer perception will also shape future adoption. Clear evidence of safety, efficacy, and absence of harmful residues will be necessary for global approval [33, 34]. Researchers should work with regulatory bodies to establish guidelines for nanobubble use in food systems, including maximum allowable concentrations, exposure limits, and quality assurance protocols. At the same time, consumer awareness campaigns will be essential to build trust and highlight the benefits of residue-free, eco-friendly preservation technologies [35, 36].

Finally, commercialization will depend on the development of cost-effective and scalable nanobubble generation systems [32, 35]. Engineering advances are needed to produce compact, energy-efficient generators that can be adopted by both large-scale commercial facilities and smallholder farmers. Partnerships between researchers, industry stakeholders, and equipment manufacturers will be critical to translating laboratory success into real-world applications. Demonstration projects and case studies across different regions and supply chains will help showcase economic benefits and encourage wider adoption [37, 38].

Conclusion

Nanobubbles represent a promising technology in post-harvest management, offering a residue-free, sustainable, and effective approach to extend shelf life, improve microbial safety, and maintain quality in fruits, vegetables, and grains. Their unique properties, including high stability, ability to generate reactive oxygen species, and impact on ethylene degradation, position them as a versatile tool for modern food systems. Applications in washing, disinfection, cold storage integration, and packaging have shown clear benefits when compared with conventional methods, particularly in reducing microbial contamination and delaying senescence. Despite these advantages, challenges remain. Standardization of nanobubble generation, scalability for industrial use, and regulatory acceptance are essential for widespread adoption. Economic considerations also need careful evaluation, particularly for small- and medium-scale producers. Addressing knowledge gaps in the mechanisms of nanobubble action and ensuring optimized

application across diverse commodities will further strengthen the case for their use. The future of nanobubble technology lies in its integration with other preservation strategies, its role in sustainable food systems, and its application beyond fruits and vegetables to include grains, cereals, and pulses. Interdisciplinary collaboration between researchers, policymakers, and industry stakeholders will be necessary to advance commercialization and ensure that the benefits of this technology are realized globally. In closing, nanobubbles hold the potential to transform post-harvest management by reducing losses, enhancing food safety, and supporting sustainability goals. With continued research, innovation, and policy support, they can contribute significantly to meeting the growing global demand for safe, high-quality, and sustainable food.

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