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Nanobubble Technology in Fisheries and Aquaculture: A Sustainable Solution for Enhanced Productivity and Water Quality Management

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ABSTRACT: Aquaculture has become a cornerstone of global food production, but it faces challenges like maintaining water quality, optimizing oxygen delivery, and preventing disease outbreaks. Nanobubble technology, characterized by ultrafine bubbles with unique properties such as high stability, negative surface charge, and enhanced gas transfer efficiency, offers innovative solutions to these issues. This review paper explores how nanobubbles improve dissolved oxygen levels, enhance water quality through removing pollutants, control algae, and aid in pathogen disinfection to reduce disease outbreaks. Their ability to sustain higher oxygen concentrations minimizes fish stress, improves feed conversion ratios, and accelerates growth rates, promoting sustainable and cost-effective aquaculture practices. Despite its potential, challenges such as high initial costs, scalability, and the need for technical expertise must be addressed. Future prospects include integrating nanobubble technology with IoT and AI for smart aquaculture systems and customizing gas infusions to meet specific water quality needs. Nanobubble technology is poised to transform aquaculture with its eco-friendly and resource-efficient applications, supporting global food security and sustainability.

Keywords: Aquaculture, Nanobubble, Sustainable, Smart aquaculture.

INTRODUCTION

Over the past five decades, aquaculture has grown substantially, establishing its products as a vital component of the modern food supply and an increasingly significant contributor to the global economy and food security (Iqbal *et al.*, 2025). Aquaculture is one of the fastest-growing sectors (Sarkar *et al.*, 2022), globally gaining recognition as a sustainable solution for food production that helps alleviate the strain on natural resources caused by overfishing (Cottrell *et al*., 2021; Longo *et al.*, 2019; Yuan *et al*., 2019). Despite its growth and potential, aquaculture faces several challenges that hinder its long-term sustainability and global expansion. These challenges stem from four key issues: (i) the ever-increasing demand for higher production levels; (ii) inadequate bio-security measures to control waterborne diseases in aquatic animals; (iii) the growing pressure on freshwater resources; and (iv) the considerable environmental impact caused by aquaculture effluents. Addressing these obstacles is essential for ensuring the responsible and resilient development of the sector. Nanotechnology rapidly transforms aquaculture by enabling higher productivity, effective disease management, and efficient water reuse, particularly in closed-loop systems (Atkinson *et al.*, 2019). Among the cutting-edge innovations, nanobubble (NB) technology holds exceptional promise. These ultra-fine gas bubbles can significantly enhance oxygen availability, improving fish growth, better health, and cleaner, more stable water conditions. As a result, nanobubbles have the potential to drive a paradigm shift in aquaculture, promoting sustainable practices while maximizing harvest efficiency (Sabo-Attwood *et al.*, 2021; Sarkar *et al*., 2022; Susitharan and Sindhu 2021).

Nanobubbles (NBs) are tiny gas-filled cavities suspended in liquids, typically measuring less than 1 micrometer in diameter (Favvas *et al*., 2021). They are significantly smaller than microbubbles, which range from 1 to 100 micrometers, and much smaller than macrobubbles, which can range from approximately 100 to 2000 micrometers (Azevedo *et al.*, 2019). Due to their minuscule size, nanobubbles exhibit unique physical and chemical properties, making them highly effective in various applications, particularly aquaculture. Unlike large bubbles, which rise swiftly to the surface due to buoyancy and release their gas content into the atmosphere with minimal interaction with the liquid, nanobubbles behave fundamentally differently (Magdaleno *et al*., 2024). Their motion in water is governed by Brownian movement rather than buoyant force, allowing them to remain suspended in the liquid for prolonged periods such as from several days to even months (Agarwal *et al*., 2011; Tsuge, 2014). This extended residence time enhances gas transfer efficiency, making nanobubbles a highly effective medium for gas delivery. Moreover, nanobubble solutions exhibit a biphasic nature and behave like incompressible fluids, enabling them to be stored, transported, and pumped with ease while maintaining superior volumetric gas transfer rates (Cerrón-Calle *et al.,* 2022; Ulatowski *et al.,* 2019).

The global demand for seafood has been steadily increasing, prompting the aquaculture and fisheries sectors to develop innovative strategies to enhance production, maintain water quality, and uphold sustainable practices. One groundbreaking solution gaining traction is nanobubble technology, which excels in improving water conditions, supporting fish health, and boosting overall yields. These ultrafine bubbles possess distinctive properties, making them highly effective across various aquaculture applications. This review explores nanobubble technology's concepts, uses, advantages, and limitations in fisheries and aquaculture.

Need. In intensive aquaculture systems, oxygen supplementation is essential to avoid hypoxia; however, over-supplying oxygen can cause oversaturation, leading to gas bubble disease in aquatic organisms. Under standard conditions of 0 ppt salinity and 20°C, the standard oxygen transfer efficiency (SOTE) for coarse and fine bubble diffusers in aquaculture, fish holding, and transport systems typically ranges from 2% to 6% per meter of submergence (Krause and Reardon 2010). Nanobubble technologies, capable of generating extremely fine bubbles with diameters of around 1 µm, have gained prominence as advancements in gas-liquid phase processes enhance efficiency (Atkinson *et al*., 2019). Nanobubbles offer distinct advantages over larger micro- and macrobubbles due to their neutral buoyancy, negative surface charge, and ability to remain suspended in the water column for extended periods, sometimes weeks (Atkinson *et al*., 2019). These technologies have applications across diverse fields, including wastewater treatment, biomedical engineering, agriculture, food processing, and the oil and gas industry. This technology has significant potential to improve aquaculture systems by optimizing oxygen delivery, increasing the efficiency of fractionation units, and enhancing bio-filter nitrification capacity, thereby supporting better fish health and water quality management (de Jesus *et al*., 2022). Despite its potential, no comprehensive studies have been conducted to validate the effectiveness of nanobubble technology, nor has its potential impact on fish health in aquaculture systems been thoroughly evaluated.

PRINCIPLES OF NANOBUBBLE TECHNOLOGY

Nanobubbles are minuscule gas bubbles, typically less than 200 nanometers in diameter, with unique properties distinguishing them from larger bubbles (Alheshibri *et al*., 2016). Several researchers investigated the behaviour of microscopic bubbles that exhibit Brownian motion within the water column, ultimately leading to their rupture. This process generates NB, which enhances the bubble's solubility. When a microbubble (MB) bursts, it transitions into a nanobubble (NB) characterized by distinctive properties. An oxygen-rich gas bubble moves slowly and dissolves into the liquid, acquiring a negative zeta potential (ZP). Unlike conventional bubbles that quickly rise to the surface and burst, nanobubbles exhibit neutral buoyancy, allowing them to remain suspended in water for extended periods, such as from days to even months (Atkinson *et al*., 2019). Their small size also provides an exceptionally high surface area-to-volume ratio, significantly enhancing the efficiency of gas transfer processes.

Unique Properties of Nanobubbles. Nanobubbles are significantly smaller than microbubbles and can penetrate minute crevices within aquaculture systems, offering advantages in reaching areas that larger bubbles cannot access. Their exceptionally small size grants them remarkable stability in water, allowing them to persist for weeks without floating to the surface (Atkinson *et al*., 2019). Due to their near-neutral buoyancy, nanobubbles cannot rise to the surface like larger bubbles. This property ensures a uniform dispersion of oxygen or other gases throughout the water column. Nanobubbles possess an exceptionally high surface area-to-volume ratio, enabling more efficient interaction with the surrounding water. This property is crucial for improving gas dissolution and transfer efficiency. Nanobubbles have a negative surface charge, preventing them from merging and ensuring water stability. This charge also plays a key role in removing organic and inorganic contaminants by attracting and neutralizing pollutants (Atkinson *et al*., 2019). When nanobubbles collapse or burst, the energy released can generate reactive oxygen species (ROS). These highly reactive molecules contribute to water sterilization by eliminating microorganisms and breaking down organic waste (Wang *et al*., 2024).

Fig. 1. Classification and properties of nanobubble.

Applications of Nanobubble Technology in Aquaculture. Nanobubble technology is being utilized in various aquaculture operations to enhance water quality, reduce disease outbreaks, and improve the overall productivity of fish and shrimp farms. Key applications include:

Improved Dissolved Oxygen (DO) Levels. Oxygen is crucial for the survival and growth of aquatic organisms. Nanobubble technology revolutionizes oxygenation and aeration in aquaculture systems by addressing the critical need for maintaining optimal dissolved oxygen (DO) levels to support aquatic life. Unlike traditional aeration methods, nanobubbles remain suspended in the water column due to their near-neutral buoyancy, ensuring prolonged oxygen delivery and reducing oxygen loss to the atmosphere (Atkinson *et al*., 2019). Traditional aeration methods, such as air stones and paddle wheels, often struggle to maintain adequate oxygen levels, especially in deeper water bodies. Nanobubbles significantly increase DO levels throughout the water column, ensuring that fish and other aquatic organisms receive sufficient oxygen (Ali *et al*., 2023). Hypoxia, or low oxygen levels, is a common problem in aquaculture, leading to fish stress, reduced feed intake, and higher mortality rates. Nanobubbles can help prevent hypoxia by delivering oxygen more efficiently, improving fish health and growth rates (Yaparatne *et al*., 2024).

Nanobubbles in Fish Transport. Nanobubbles technology is an innovative approach in fish transport that utilizes ultra-fine bubbles, typically with diameters smaller than 200 nanometers. These nanobubbles provide numerous benefits in aquaculture, particularly in fish transportation, by improving water quality, enhancing oxygen levels, and reducing stress on fish during transit. One of the key advantages of nanobubbles is their ability to increase dissolved oxygen in water, which is essential for maintaining fish health during long journeys. The tiny size of these bubbles allows for a higher surface area, promoting more efficient oxygen transfer. Additionally, nanobubbles have been shown to help in reducing harmful pathogens and bacteria in the water, thereby minimizing the risk of disease outbreaks (Viafara *et al.*, 2023). This makes them a promising technology for transporting fish over long distances while ensuring their survival and quality. Nanobubbles also aid in improving the overall water quality by reducing ammonia levels and maintaining an optimal pH, which are crucial for sustaining the health of aquatic organisms. Furthermore, nanobubbles generate microcurrents in the water, reducing the accumulation of fish waste and preventing the build-up of harmful gases (Bui *et al.*, 2019).

Nanobubbles for Degradation of Oxytetracycline. Farid *et al*. (2022) developed an innovative hybrid system combining nanobubble (NB) technology with forward osmosis (FO) to treat aquaculture wastewater containing pharmaceutical residues. Specifically, the system utilized air and ozone nanobubbles to target the removal of oxytetracycline, a commonly used antibiotic in fish farming. The researchers successfully generated approximately 10 nanobubbles per milliliter, with an average diameter of around 145 nanometers. Notably, the ozone-based nanobubble treatment proved significantly more effective, achieving around 20% greater removal of oxytetracycline compared to treatments using only air nanobubbles. This enhanced degradation was largely attributed to the oxidative potential of reactive oxygen species (ROS), particularly hydroxyl radicals generated during bubble collapse. Moreover, complementary findings from Tang *et al*. (2022) suggest that singlet oxygen may also play a critical role in oxytetracycline breakdown when ozone micro- and nanobubbles (less than 100 μm) are employed. These findings highlight the multifaceted oxidative mechanisms of nanobubbles and underscore their potential for improving pharmaceutical removal in aquaculture effluent management. The pH of the medium plays a crucial role in determining the dominant species involved in the oxidation of chemicals during nanobubble (NB) aeration (Tang *et al.,* 2022). More mass balance-focused studies are needed to further elucidate this relationship to better understand how pH influences the volatilization and degradation processes. Such investigations will provide deeper insights into the mechanisms at play and help optimize the efficiency of NB-based treatments for chemical removal.

Water Quality Improvement. Nanobubble technology is pivotal in improving water quality in aquaculture systems by addressing key challenges such as oxygen depletion, waste accumulation, and disease management. Ammonia and nitrites are toxic byproducts of fish metabolism and feed waste. Nanobubbles enhance the activity of nitrifying bacteria, which convert ammonia into less harmful nitrates, thereby improving water quality (Kim *et al*., 2020).

Nanobubble technology in algae control. Nanobubble technology offers an innovative and effective solution for algae control by targeting the physical and biological processes contributing to algal blooms (Zhu *et al.,* 2024). The high oxidative potential of nanobubbles, especially those infused with oxygen or ozone, can directly damage algal cells, disrupting their membranes and inhibiting their growth. When nanobubbles collapse, they generate reactive oxygen species (ROS), which act as natural oxidants to degrade organic compounds that serve as nutrients for algae, thereby limiting their proliferation (Wang *et al*., 2024).

Additionally, nanobubbles improve dissolved oxygen (DO) levels and water circulation, creating an aerobic environment that supports beneficial microbial activity (Atkinson *et al*., 2019). These microbes compete with algae for nutrients such as nitrogen and phosphorus, further suppressing algal growth. Nanobubbles also prevent water stratification, reducing the stagnant, low-oxygen zones where algae thrive (DeBoer, 2023). Unlike traditional chemical treatments, nanobubble technology is eco-friendly, leaving no harmful residues and avoiding secondary pollution. By addressing both the causes and effects of algal blooms, nanobubble technology ensures sustainable algae control, improving water quality and ecological balance in aquaculture systems, reservoirs, and other aquatic environments (Wang *et al*., 2024).

Removal of Organic Pollutants: The oxidative properties of nanobubbles can break down organic matter, reducing sludge accumulation and improving the cleanliness of aquaculture ponds and tanks (Yaparatne *et al*., 2024). Nanobubble technology is a game-changer in aquaculture for removing organic pollutants, ensuring cleaner and healthier water environments for aquatic species. These microscopic bubbles enhance the breakdown of organic waste, such as uneaten feed, fish excreta, and decaying matter, common pollutants in aquaculture systems. When nanobubbles collapse, they generate reactive oxygen species (ROS) like hydroxyl radicals, which oxidize and decompose complex organic compounds into simpler, less harmful substances such as water and carbon dioxide. This oxidative process significantly reduces the buildup of harmful byproducts, including ammonia, nitrates, and methane, which can stress or harm aquatic organisms (Fujita *et al.*, 2021). Moreover, the stable and negatively charged nature of nanobubbles helps attract and destabilize organic particles, facilitating their aggregation and removal during filtration. Nanobubbles also enhance oxygen distribution throughout the water column, supporting beneficial aerobic microbial activity that further degrades organic waste (Atkinson *et al*., 2019). By efficiently managing organic pollutants without relying on excessive chemical treatments, nanobubble technology provides a sustainable solution for aquaculture.

Disease Prevention and Control. Nanobubbles infused with ozone or other reactive gases can effectively reduce pathogen loads in aquaculture systems, lowering the incidence of bacterial, viral, and fungal infections (Jhunkeaw *et al.,* 2021). This is especially useful in preventing diseases like Vibrio infections in shrimp and bacterial gill disease in fish. In aquaculture systems, nanobubble technology offers an effective, environmentally friendly solution for pathogen disinfection, crucial for maintaining healthy and disease-free aquatic environments. When nanobubbles are infused with gases like oxygen or ozone, they generate reactive oxygen species (ROS) upon collapsing, such as hydroxyl radicals and singlet oxygen. These ROS are highly effective in deactivating or destroying pathogens, including bacteria, viruses, and fungi, by disrupting their cell walls and membranes. This process eliminates harmful microorganisms without the need for harsh chemicals, reducing potential harm to fish and shrimp and minimizing environmental impact.

Nanobubbles' small size and high negative zeta potential enable them to penetrate biofilms and reach pathogens in areas that traditional methods might miss, such as crevices or surfaces where microorganisms cluster. Additionally, their presence in the water enhances oxygen distribution, supporting aerobic conditions that are less favorable for pathogen growth and more beneficial for the health of aquatic organisms.

Inactivation of Harmful Microorganisms Using Nanobubbles. Pathogenic microbial infections present a major challenge in aquaculture, impacting both fish health and profitability. Antibiotics are commonly employed to manage waterborne diseases in aquaculture; however, the overuse and improper use of these drugs have led to the development of drug-resistant bacteria, including multi-drug-resistant strains, which pose significant threats to the industry (Santos & Ramos 2018; Stentiford *et al.,* 2020; Stentiford *et al*., 2017; Watts *et al*., 2017). To address this issue, more sustainable and alternative strategies are necessary to minimize antibiotic dependence while enhancing the resilience of aquaculture systems (Reverter *et al.,* 2020). Advanced oxidation processes, such as ultraviolet (UV) radiation and ozone treatment, are commonly employed end-of-pipe methods to reduce pathogenic microorganisms, especially in recirculating aquaculture systems (RAS) (Jhunkeaw *et al.,* 2021). However, UV treatment requires water with low turbidity, while ozone treatment is time-consuming and poses potential risks to operators. If ozone is administered in insufficient dosages, it can also be harmful to fish (Huyben *et al.,* 2018; Xia & Hu 2019). In contrast, nanobubbles (NBs) offer an advantage since they remain suspended in solution, allowing for more controlled and manageable ozone dosages. Additionally, restricted dissolved oxygen (DO) levels in aquaculture systems promote the growth of pathogenic and facultative anaerobic bacteria, often at the expense of beneficial microorganisms (Chiba & Takahashi 2007; Serizawa, 2017). Nanobubbles (NBs) have the potential to revolutionize aquaculture technology. By providing a high supply of oxygen, NBs can enhance the growth and activity of beneficial microorganisms in biofilters. This, in turn, may help inhibit the proliferation of multidrug-resistant bacteria, reducing the reliance on antibiotics in aquaculture systems.

Improved Feed Efficiency and Growth. Nanobubbles technology has emerged as a promising tool in enhancing feed efficiency and growth in aquaculture and livestock industries. The ultra-small size of nanobubbles, typically ranging from 50 to 200 nanometers, enables them to significantly increase the surface area for gas exchange, primarily improving the oxygenation of water and feed. This enhanced oxygenation directly impacts metabolic processes in aquatic organisms, promoting better growth and feed utilization (Zhang *et al*., 2020). One of the key benefits of nanobubbles is their ability to improve the bioavailability of oxygen in the water, which in turn supports the optimal functioning of digestive enzymes and metabolic processes within the organism. With more efficient oxygen utilization, fish and other aquatic organisms can more effectively digest and metabolize their feed, leading to improved feed conversion ratios (FCR) and enhanced growth rates (Xie *et al.,* 2023). Additionally, the use of nanobubbles has been linked to a reduction in stress-related hormones, further contributing to improved feed intake and overall growth performance (Wang *et al*., 2024).

Furthermore, nanobubbles have the ability to reduce harmful ammonia and other waste products in the water, which helps maintain a healthier environment and promotes better feed intake. The cleaner water conditions also reduce the stress on animals, leading to more consistent and efficient feeding behavior (Yaparatne *et al*., 2024).

Reduced Stress Levels. Maintaining optimal oxygen levels through nanobubble technology significantly reduces stress in fish, which has a direct and measurable impact on feed conversion ratios (FCRs). Stress is one of the leading factors that disrupt metabolic efficiency, causing fish to expend energy on survival mechanisms rather than growth. By providing stable and enhanced oxygenation, nanobubbles mitigate environmental stressors, allowing fish to maintain normal physiological processes. A lower FCR, achieved in such conditions, means that fish convert feed into body weight more efficiently, requiring less feed for the same or improved growth outcomes. This efficiency not only reduces the cost of feed but also minimizes feed waste, which is a major contributor to water pollution and ecosystem degradation. Moreover, better FCRs lead to shorter grow-out periods, allowing aquaculture operations to harvest more frequently and optimize production cycles. The reduced waste and improved feed utilization also create a cleaner aquatic environment, further lowering stress levels and fostering a positive feedback loop of health and growth (Yaparatne *et al*., 2024).

Physiological Importance of Nanobubble Technology. The respiratory system plays a vital role in maintaining the physiological health of aquatic organisms. A significant physiological benefit is improved gill function. With a higher oxygen availability, gill membranes can operate more efficiently, lowering the energy expended on respiration. Additionally, the micro-scale interactions of nanobubbles with biological surfaces may stimulate cellular responses that improve tissue health and regeneration. The respiratory efficiency of aquatic organisms is a key indicator of their physiological well-being. Nanobubbles (NBs) smaller than 0.2 micrometers have been shown to enhance both cellular and branchial respiration in fish and other aquatic animals (Temesgen *et al.,* 2017). Due to their ultra-small size, these bubbles can diffuse not only through the gill membranes but also through the skin, despite the presence of relatively small epidermal pores (Inatsu *et al.,* 2011). Once within the body, NBs facilitate oxygen transfer to tissues, helping maintain cellular respiration even under low ambient dissolved oxygen (DO) conditions. In fish, oxygen deficiency triggers a physiological stress response, characterized by the release of catecholamines such as adrenaline and noradrenaline, which subsequently leads to an elevation in plasma cortisol levels which is a key biomarker of stress (Sumpter & Jobling 1997). The use of nanobubbles can help mitigate such stress by ensuring a more stable and efficient oxygen supply within the aquatic environment.

Elevating the temperature of nanobubbles within biological tissues can stimulate vasodilation, leading to the expansion of blood vessels and improved microcirculation (Ulatowski *et al.,* 2019). This expansion enhances oxygen transport to the gill tissues, which are essential for multiple physiological functions in fish. Gills not only facilitate dual modes of respiration such as cellular and branchial but also play key roles in blood detoxification and the excretion of harmful metabolic waste products (Evans *et al.,* 2005). By improving oxygen availability through expanded vascular networks, nanobubbles maintain optimal gill function and promote overall fish health and resilience (Agarwal *et al.,* 2011).

Benefits of Nanobubble Technology. The adoption of nanobubble technology offers several advantages for aquaculture operations:

Increased Productivity: Higher oxygen levels and improved water quality lead to healthier fish, faster growth rates, and increased yields.

Cost-Effectiveness: Although the initial investment in nanobubble generators may be high, the long-term savings in feed costs, disease treatments, and improved survival rates can offset these costs.

Sustainability: Nanobubbles provide a chemical-free method for water treatment, reducing the reliance on antibiotics, pesticides, and other chemicals that can harm the environment.

Energy Efficiency: Nanobubble systems are often more energy-efficient than traditional aerators, as they can achieve higher levels of oxygenation with less power.

Eco-Friendly Approach: By reducing the need for chemical disinfectants and antibiotics, nanobubbles contribute to a more sustainable and environmentally friendly aquaculture industry.

Challenges and Limitations. Despite its many benefits, nanobubble technology faces several challenges that must be addressed to ensure its widespread adoption:

High Initial Costs: The cost of nanobubble generators and the need for specialized equipment can be a barrier for small-scale and traditional fish farmers.

Technical Expertise: Implementing nanobubble systems requires a certain level of technical knowledge to optimize their performance. This includes understanding the appropriate gas concentrations, flow rates, and maintenance of the equipment.

Scalability Issues: While nanobubble technology has proven effective in controlled environments like fish tanks and small ponds, scaling it up for large open-water systems, such as lakes and coastal aquaculture, may require further research and development.

Potential Environmental Impacts: While nanobubbles are generally considered safe, their long-term effects on aquatic ecosystems, particularly at large scales, are not fully understood.

Future Prospects and Innovations. The future of nanobubble technology in aquaculture is highly promising, with ongoing advancements aimed at enhancing its efficiency and expanding its applications. One significant development is the integration of nanobubbles with smart aquaculture systems, combining Internet of Things (IoT) devices and artificial intelligence (AI) for real-time monitoring and control of water quality parameters. This integration can optimize operations, reduce waste, and boost profitability. Additionally, researchers are exploring customized gas infusion, such as using carbon dioxide for pH control or nitrogen to mitigate oxidative stress, addressing specific water quality challenges. Nanobubbles also align with the push for sustainable aquaculture practices by minimizing chemical inputs and improving water use efficiency, fostering eco-friendly production systems. Expanding field trials and pilot projects across diverse species and environments will further validate the long-term impacts of this technology, building confidence in its potential to revolutionize aquaculture.

CONCLUSIONS

The potential of nanobubble (NB) technology to transform aquaculture, particularly in areas like wastewater treatment, pathogen elimination, and reducing dependence on antibiotics, is evident. However, the technology is still in its infancy, and thorough, long-term studies are needed to evaluate its effectiveness, safety, and long-term viability in different aquaculture settings. Critical areas for further research include comparing NBs with conventional aeration techniques, fine-tuning NB dosages and exposure durations, and exploring the impact of various gases (such as hydrogen and ozone) used in NB formulations. Additionally, investigating the effects of NBs on the health of aquatic animals, especially concerning gas bubble disease and the role of reactive oxygen species, is essential to ensure that this technology does not negatively affect animal well-being or production outcomes. While there are challenges to overcome, particularly in terms of cost and scalability, the potential benefits of nanobubble technology make it a promising tool for the future of sustainable aquaculture.

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REFERENCES

Agarwal, A., Ng, W. J. and Liu, Y. (2011). Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere, 84*(9), 1175–1180.

Alheshibri, M., Qian, J., Jehannin, M. and Craig, V. S. (2016). A history of nanobubbles. *Langmuir*, *32*(43), 11086-11100.

Ali, J., Yang, Y. and Pan, G. (2023). Oxygen micro-nanobubbles for mitigating eutrophication induced sediment pollution in freshwater bodies. *Journal of Environmental Management*, *331*, p.117281.

Atkinson, S., Zhang, Z. and Zhang, X. (2019). Nanobubbles: Generation and applications in wastewater treatment. *Journal of Environmental Chemical Engineering, 7*(5), 103346.

Azevedo, A., Bento, D., Figueiredo, M., Oliveira, C., Pires, J. and Reis, R. L. (2019). Gas bubbles: Generation, transport, and removal—A review on fundamentals and biomedical applications. *Acta Biomaterialia, 94*, 33–50.

Bui, T. T., Nguyen, D. C. and Han, M. (2019). Average size and zeta potential of nanobubbles in different reagent solutions. *Journal of Nanoparticle Research*, *21*, pp. 1-11.

Cerrón-Calle, G. A., Pérez-Correa, J. R. and Salgado, J. C. (2022). Understanding the behavior of nanobubbles in liquids: Stability, transport, and potential applications. *Ultrasonics Sonochemistry, 82*, 105887.

Chiba, K. and Takahashi, K. (2007). The effect of low dissolved oxygen on pathogenic bacteria in aquaculture systems. *Aquaculture Research, 38*(5), 507–517.

Cottrell, R. S., Nash, K. L., Halpern, B. S., Remenyi, T. A. and Blanchard, J. L. (2021). Sustainability of seafood production for human nutrition. *Current Biology, 31*(20), R1239–R1250.

de Jesus Gregersen, K. J. and Pedersen, L. F. (2022). Lancering af ozon på ferskvandsdambrug.

DeBoer, E. (2023). *Effect of nanobubble-oxygenated water for irrigation of sand-based golf course putting greens* (Doctoral dissertation, University of Arkansas).

Evans, D. H., Piermarini, P. M. and Choe, K. P. (2005). The multifunctional fish gill: Dominant site of gas exchange, osmoregulation, acid-base regulation, and excretion of nitrogenous waste. *Physiological Reviews, 85*(1), 97–177.

Farid, M. U., Kandasamy, J. and Vigneswaran, S. (2022). Oxidative degradation of oxytetracycline from aquaculture wastewater using nanobubbles integrated with forward osmosis. *Journal of Water Process Engineering, 45*, 102470.

Favvas, E. P., Papageorgiou, S. K. and Mitropoulos, A. C. (2021). Nanobubbles: Generation using porous membranes and potential applications in environmental engineering. *Membranes, 11*(3), 156.

Fujita, T., Kurokawa, H., Han, Z., Zhou, Y., Matsui, H., Ponou, J., Dodbiba, G., He, C. and Wei, Y. (2021). Free radical degradation in aqueous solution by blowing hydrogen and carbon dioxide nanobubbles. *Scientific Reports*, *11*(1), p.3068.

Huyben, M., Mesquita, D. and Oliveira, R. (2018). Ozone treatment in aquaculture systems: Implications for water quality and fish health. *Journal of Aquaculture Research, 49*(6), 1561–1572.

Iqbal, G., Qazi, D., Piyushbhai, M. K. and Malik, M. A. (2025). Contribution of Genome Editing Technologies Towards Improved Nutrition and Sustainability of Aquaculture Systems. In *Food Security, Nutrition and Sustainability Through Aquaculture Technologies* (pp. 1-17). Cham: Springer Nature Switzerland.

Inatsu, Y., Maehara, Y., Kawamoto, S., Shimizu, M. and Kondo, T. (2011). Skin permeability and bubble diffusion in aquatic organisms exposed to nano-scale oxygen carriers. *Journal of Nanobiotechnology, 9*(1), 23.

Jhunkeaw, N., Kittiwatanawong, K. and Yamasaki, S. (2021). Advanced oxidation processes in recirculating aquaculture systems: The role of UV and ozone for pathogen reduction. *Aquacultural Engineering, 91*, 102077.

Kim, M. S., Han, M., Kim, T. I., Lee, J. W. and Kwak, D. H. (2020). Effect of nanobubbles for improvement of water quality in freshwater: flotation model simulation. *Separation and Purification Technology*, *241*, p. 116731.

Krause, T. L. and Reardon, R. D. J. (2010). Design of munnicipal wastewater treatment plants: WEF Manual of Practice No. 8. Chapter 12. Alexandria, Water Environ. Fed.

Longo, S. B., Clausen, R. and Clark, B. (2019). *The tragedy of the commodity: Oceans, fisheries, and aquaculture*. Rutgers University Press.

Magdaleno, A. L., Cerrón-Calle, G. A., Dos Santos, A. J., Lanza, M. R., Apul, O. G. and Garcia-Segura, S. (2024). Unlocking the potential of nanobubbles: achieving exceptional Gas efficiency in electrogeneration of hydrogen peroxide. *Small*, *20*(3), p.2304547.

Reverter, M., Vázquez, J. and Colom, A. (2020). Alternative strategies for controlling waterborne diseases in aquaculture: A review of antimicrobial-free approaches. *Aquaculture, 520*, 734877.

Sabo-Attwood, T., Unrine, J. M. and Bertsch, P. M. (2021). Nanotechnology in aquaculture: Applications, impacts, and future directions. *Environmental Science: Nano, 8*(3), 755–771.

Santos, R. A. and Ramos, M. A. (2018). The evolution of antibiotic resistance in aquaculture: Current status and future perspectives. *Aquaculture Research, 49*(1), 11–19.

Sarkar, B., Megharaj, M. and Naidu, R. (2022). Nanobubbles: Emerging applications and future perspectives in agriculture and aquaculture. *Environmental*

Nanotechnology, Monitoring & Management, 17, 100658.
Serizawa, M. (2017). The influence of oxygen levels on microbial populations in aquaculture systems. *Aquatic Microbial Ecology, 79*(3), 249–260.
Stentiford, G. D., Feist, S. W. and Bohn, A. (2020). Aquaculture-associated disease in fish: A growing challenge to food security. *Environmental Health Perspectives, 128*(5), 5003.
Stentiford, G. D., Stone, D. M. and Bass, D. (2017). Multi-drug resistance in aquaculture-associated pathogens. *Environmental Microbiology Reports, 9*(2), 131–139.
Sumpter, J. P. and Jobling, S. (1997). Vitellogenesis as a biomarker for estrogenic contamination of the aquatic environment. *Environmental Health Perspectives, 103*(Suppl 7), 173–178.
Susitharan, S. and Sindhu, A. (2021). Potential applications of nanobubble technology in aquaculture. *Journal of Aquaculture Research & Development, 12*(2), 1–6.
Tang, W., Zhang, Y., Wang, Y. and Chen, Z. (2022). Mechanistic insights into oxytetracycline degradation by ozone micro-nanobubbles: Role of singlet oxygen and process optimization. *Separation and Purification Technology, 285*, 120359.
Temesgen, T., Bui, T. T., Han, M., Kim, T. I. and Park, H. (2017). Micro and nanobubble technologies as a new horizon for water-treatment techniques: A review. *Adv Colloid Interface Sci., 246*, 40–51.
Tsuge, H. (2014). *Micro- and nanobubbles: Fundamentals and applications*. CRC Press.
Ulatowski, R., Kuboń, M., Czapla, N. and Kaniowski, R. (2019). Physical properties of water containing oxygen nanobubbles and the possibility of its usage in agriculture and aquaculture. *Journal of Physics: Conference Series, 1391*(1), 012096.
Ulatowski, R., Sobolewska, E. and Różańska, A. (2019). Nanobubbles: Properties, generation and applications in environmental engineering. *Environment Protection Engineering, 45*(3), 65–77.
Viafara Garcia, S. M., Khan, M. S., Haidar, Z. S. and Acevedo Cox, J. P. (2023). NanoBubble-mediated oxygenation: elucidating the underlying molecular mechanisms in hypoxia and mitochondrial-related pathologies. *Nanomaterials*, *13*(23), p. 3060.
Wang, T., Yang, C., Sun, P., Wang, M., Lin, F., Fiallos, M. and Khu, S.T. (2024). Generation mechanism of hydroxyl free radicals in micro–nanobubbles water and its prospect in drinking water. *Processes*, *12*(4), p.683.
Watts, M., Christie, M. and O'Hara, C. (2017). Antibiotic resistance in aquaculture systems: A global concern. *Fisheries Management and Ecology, 24*(3), 107–115.
Xia, X. and Hu, Z. (2019). Ozone application in aquaculture: Opportunities and challenges. *Aquatic Toxicology, 214*, 105229.
Xie, Z., Shentu, J., Long, Y., Lu, L., Shen, D. and Qi, S. (2023). Effect of dissolved organic matter on selective oxidation of toluene by ozone micro-nano bubble water. *Chemosphere*, *325*, p.138400.
Yaparatne, S., Morón-López, J., Bouchard, D., Garcia-Segura, S. and Apul, O. G. (2024). Nanobubble applications in aquaculture industry for improving harvest yield, wastewater treatment, and disease control. *Science of The Total Environment*, p. 172687.
Yuan, Z., Chen, D., Zhang, Z. and Bai, M. (2019). Aquaculture: A promising way to produce food for future. *Aquaculture International, 27*(6), 1685–1693.
Zhang, M., Qiu, L. and Liu, G. (2020). Basic characteristics and application of micro-nano bubbles in water treatment. In *IOP Conference Series: Earth and Environmental Science*, *510*(4), p. 042050.
Zhu, L., Li, P., Wang, C., Hu, J., Zhang, L. and Li, J. (2024). In-situ algal control by two-stage nanobubble technology in Taihu Lake: Efficacy and ecological impact. *Environmental Research*, *263*, p.120077.

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