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NANOBUBBLE TECHNOLOGY: AN EMERGING INNOVATION FOR SUSTAINABLE SHRIMP AQUACULTURE

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The use of shrimp aquaculture has increased rapidly across the world and contributes a large portion of the global food supply of seafood. However, shrimp production tends to have very significant challenges such as poor water conditions, diseases, inefficient aeration and the negative impact of aquaculture on the environment. New technologies—including the use of nanobubble technology—can help solve these issues within shrimp aquaculture through their ability to improve water quality, oxygen transfer and microbial activity in aquaculture ponds. The positive characteristics of nanobubbles (that are generally 200 nanometers or less in size) are due in large part to their unique physicochemical properties of high stability, large surface area and strong oxidative potential,which can have a positive impact on shrimp development, immune system status and pond ecosystem stability while also decreasing pathogenic microorganisms. Research has shown that these benefits will also translate into significant economic and environmental advantages for the sustainable growth of shrimp aquaculture. In conclusion, this article highlights the principles, mechanisms, applications, advantages, and constraints of nanobubble technology used in shrimp aquaculture and outlines the transformative impact of nanobubble technology on the productivity and sustainability of modern aquaculture systems.

Aquaculture plays an important role in global food production as seafood demand increases and natural fish stocks decline. Shrimp aquaculture, particularly the culture of Litopenaeus vannamei, is a major sector contributing to the economies of many countries. However, intensive shrimp farming faces challenges such as poor water quality, oxygen depletion, disease outbreaks, and organic waste accumulation in ponds. Conventional aeration systems, including paddlewheel aerators and diffused air systems, are widely used to supply oxygen, but they often have low oxygen transfer efficiency, creating stressful conditions for shrimp.

Recent advances in nanotechnology have introduced nanobubble technology as an effective solution in aquaculture. Nanobubbles are ultra-fine gas bubbles with high stability and unique physical properties compared to conventional bubbles. They improve oxygen transfer, stimulate beneficial microorganisms, and help control disease-causing pathogens in aquatic systems. Studies have shown that nanobubble technology can enhance shrimp growth, improve pond water quality, and increase disease resistance, making it a promising approach for sustainable aquaculture.

Principles and Characteristics of Nanobubbles

Nanobubbles are tiny gas bubbles in the water with diameters that are generally smaller than 200 nanometers in diameter. Unlike other types of bubbles, which rise to the surface of the water and burst after some time, nanobubbles are highly stable and can float in the water for long periods of time. One of the most unique characteristics of nanobubbles is their large surface area to volume ratio. This enables them to dissolve more gases in water compared to other types of bubbles. Oxygen nanobubbles are thus highly effective in increasing the concentration of dissolved oxygen in water. Another unique feature of nanobubbles is their negative surface charge, also known as zeta potential. This enables them to repel each other and hence do not coagulate easily in water. Another unique feature of nanobubbles is their highly oxidative properties, which are released when the nanobubbles burst and release hydroxyl radicals, which have highly potent antimicrobial properties and can destroy harmful microbes in the aqua environment.

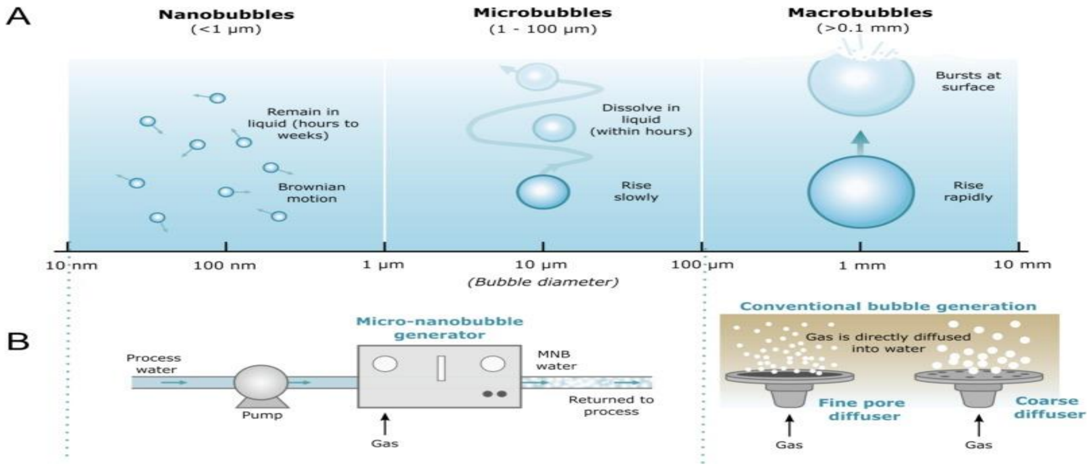

Fig. 1: Comparative characteristics and generation methods of bubbles across scales.

Mechanisms of Nanobubble Technology in Aquaculture

Nanobubble technology affects aquaculture systems in different ways, either biologically, chemically, or physically. One of the ways in which nanobubble technology affects aquaculture is by improving the efficiency of the transfer of oxygen in water. The small size and stability of nanobubbles mean that they dissolve in water over time, allowing the slow release of oxygen into the water column, which is essential for the metabolism and growth of aquatic life (Khan et al., 2022). Another way in which nanobubble technology affects aquaculture is by improving the growth of beneficial microorganisms in aquaculture ponds. The improved level of oxygen in aquaculture systems, which is brought about by nanobubble technology, improves the growth of aerobic microorganisms that help in the breakdown of organic matter and the conversion of toxic nitrogen compounds such as ammonia into harmless compounds. Additionally, there is enhanced sediment oxygenation with reduced production of toxic gases such as hydrogen sulfide. With increased oxygen levels in the pond bed, there is enhanced activity of beneficial microorganisms that degrade organic materials (Zhou et al., 2022). Another significant action of nanobubbles is in controlling pathogens. The oxidative properties of nanobubbles have been known to disrupt microbial cell membranes, thereby controlling the development of harmful bacteria and viruses that cause diseases in aquaculture (Garcia-Segura et al., 2023).

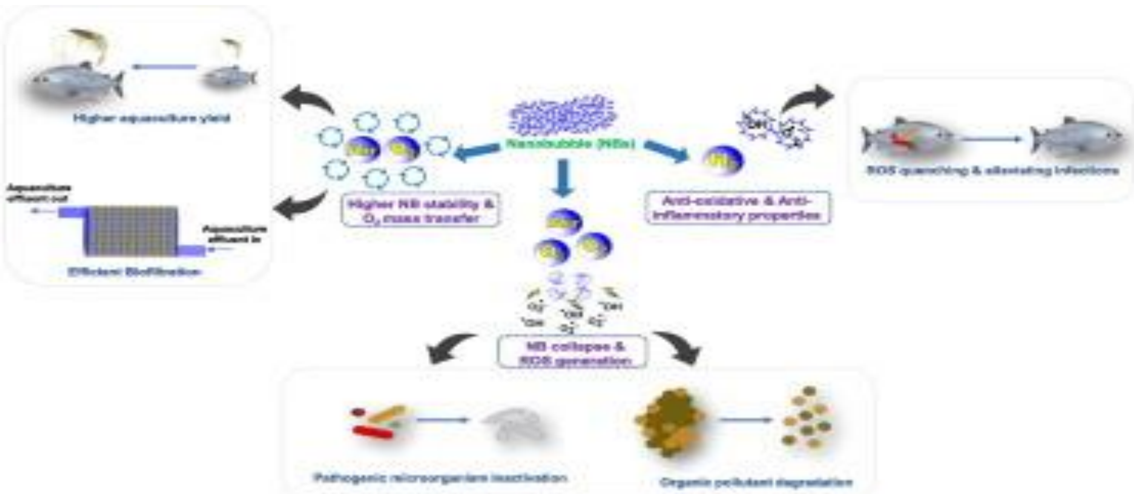

Fig. 1a: Physicochemical properties and biological mechanisms of nanobubbles in aquaculture systems

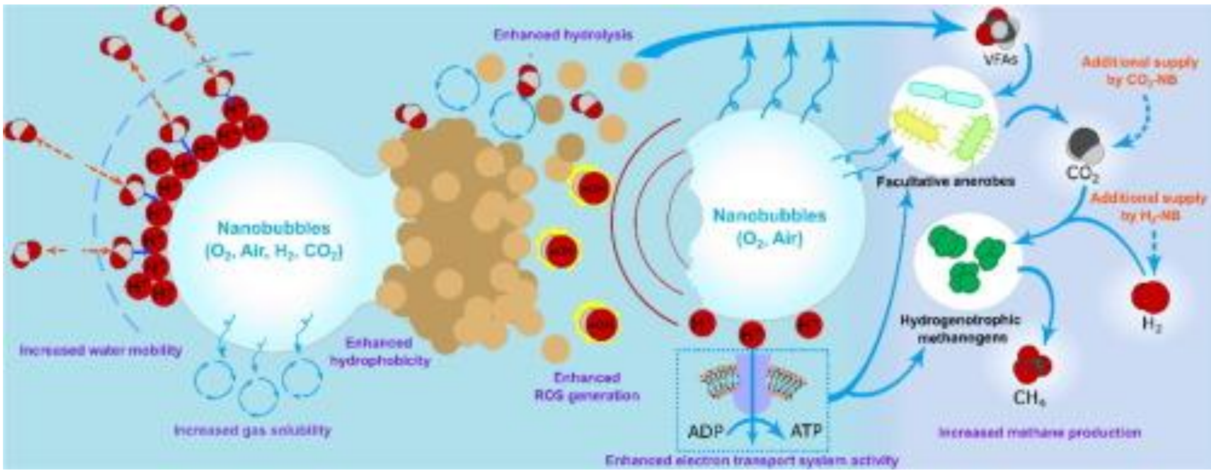

Fig. 2b: Mechanisms of nanobubbles in enhancing microbial activity and methane production.

Role of Nanobubble Technology in Shrimp Aquaculture

Nanobubble technology involves the use of ultra-fine gas bubbles (<200 nm) that remain suspended in water for long periods, supporting physical, chemical, and biological processes in aquaculture systems. In shrimp farming, nanobubbles help maintain dissolved oxygen, reduce organic waste, improve disease control, and enhance overall productivity. Intensive shrimp culture systems often face challenges such as oxygen depletion, waste accumulation, and pathogen outbreaks. Nanobubbles, generated from compressed air or oxygen, provide continuous aeration and improve water quality in systems culturing Pacific white shrimp Litopenaeus vannamei (Temesgen et al., 2021; Khan et al., 2022). One major benefit of nanobubble technology is improved dissolved oxygen availability. Unlike conventional aeration, where larger bubbles quickly escape to the atmosphere, nanobubbles dissolve slowly and distribute oxygen uniformly throughout the pond. This helps maintain adequate oxygen levels required for shrimp respiration, metabolism, and energy production, thereby reducing stress conditions (Choi et al., 2021).

Nanobubbles also improve water quality by enhancing oxygenation in water and sediments. Intensive shrimp farming produces large amounts of organic waste such as uneaten feed, feces, and microbial residues, which can generate toxic compounds including ammonia, nitrite, and hydrogen sulfide. Nanobubble systems stimulate beneficial microorganisms that decompose organic matter and convert harmful compounds into less toxic forms, improving nutrient cycling and pond balance (Wang et al., 2023). In addition, nanobubbles positively influence microbial communities in pond water, sediments, and shrimp intestines. Beneficial microorganisms support digestion, nutrient metabolism, and immune responses in shrimp.

Studies indicate that nano-aeration systems increase beneficial bacterial populations, improve gut microbiota balance, and enhance nutrient utilization and disease resistance in shrimp (Xu et al., 2022).

Nanobubble technology is also effective in pathogen control, particularly when combined with ozone. Ozone nanobubbles generate reactive oxygen species such as hydroxyl radicals that damage microbial cell membranes and suppress pathogen growth. This reduces the risk of bacterial diseases and economic losses in shrimp aquaculture (Liu et al., 2021; Garcia-Segura et al., 2023).The use of ozone nanobubbles has been reported to improve growth performance, feed conversion efficiency, survival rate, and gut microbial balance in Litopenaeus vannamei culture systems by improving water quality and reducing microbial contamination (Phan et al., 2024).Furthermore, oxygen nanobubble systems contribute to ecosystem stability in shrimp ponds by maintaining dissolved oxygen, promoting microbial activity, and reducing harmful metabolites. These effects support sustainable shrimp farming and long-term aquaculture productivity (Zhang et al., 2024).Overall, nanobubble technology offers several advantages in shrimp aquaculture, including enhanced oxygen transfer, improved water quality, beneficial microbial development, pathogen reduction, and better shrimp growth performance, making it an important tool for sustainable aquaculture production (Yaparatne et al., 2024; Sravani et al., 2024).

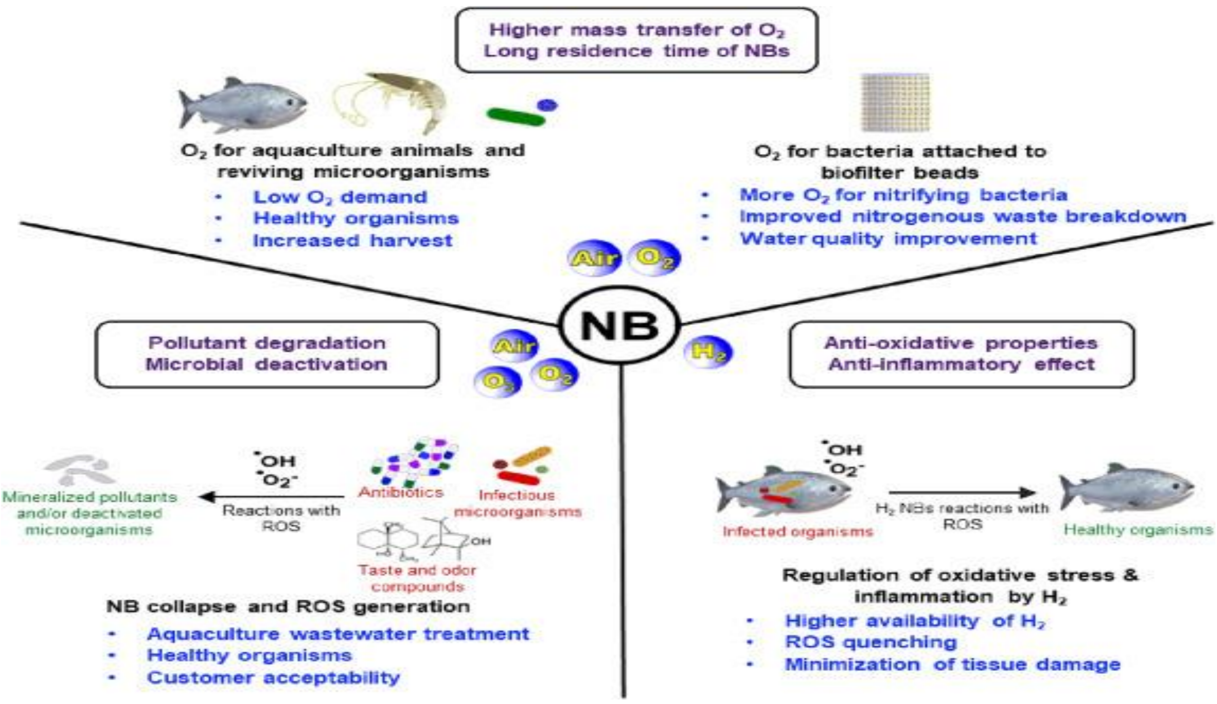

Fig. 3: Functional roles of nanobubbles in shrimp aquaculture systems.

Applications in Shrimp Aquaculture

In shrimp aquaculture, nanobubble technology has numerous real-world uses. The first is the use of oxygen nanobubble aeration to enhance dissolved oxygen levels and support shrimp growth and immunities in culture ponds https://doi.org/10.1016/j.aquaculture.2024.738715 (Zhang et al., 2024). Another application is using ozone nanobubbles for disinfecting water and controlling pathogen populations. Due to the high antimicrobial effect of ozone nanobubbles, they can substantially decrease bacterial numbers in shrimp farms (Phan et al., 2024). Nanobubbles can also be utilized in biofloc systems. Biofloc systems utilize microbial communities to recycle nutrients and transform organic waste into microbial biomass, which the shrimp can eat. The addition of nanobubble aeration increases microbial activity and nutrient recycling efficiency in biofloc systems (Liang et al., 2025). Nanobubbles have alsobeen utilized in aquaculture systems to treat wastewater, which enhances water reuse and minimizes environmental contamination (Yaparatne et al., 2024).

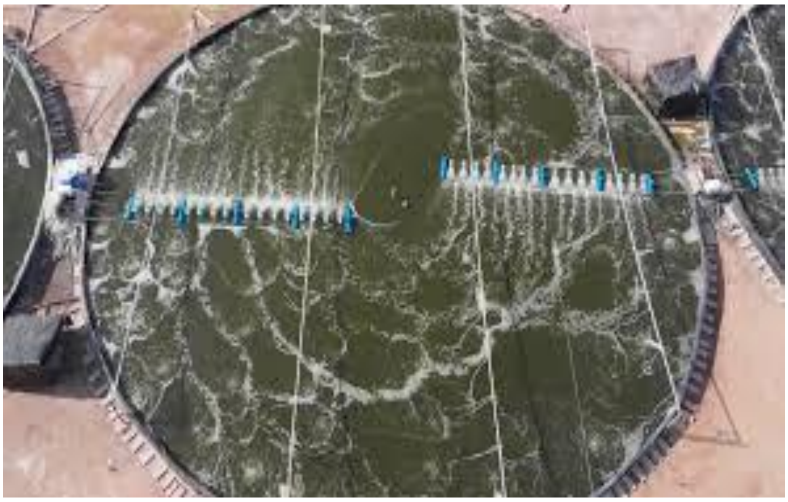

Fig. 4: Field-scale application of nanobubble aeration in shrimp aquaculture ponds.

Advantages of Nanobubble Technology in Shrimp Farming

Nanobubble technology provides several benefits for shrimp farming. The first major advantage is that it provides improved efficiency in oxygen transfer, which is much higher than that of traditional aerators (Khan et al., 2022). This is due to the fact that it enhances aerobic microbial action, which in turn hastens the rate of decomposition of organic waste materials in ponds (Zhou et al., 2022). Another major advantage is that it provides antimicrobial action that is capable of controlling disease-causing organisms in shrimp farming (Garcia-Segura et al., 2023). Moreover, nanobubble technology provides improved growth performance in shrimp, which in turn translates into increased production yields for shrimp farmers (Zhang et al., 2024).

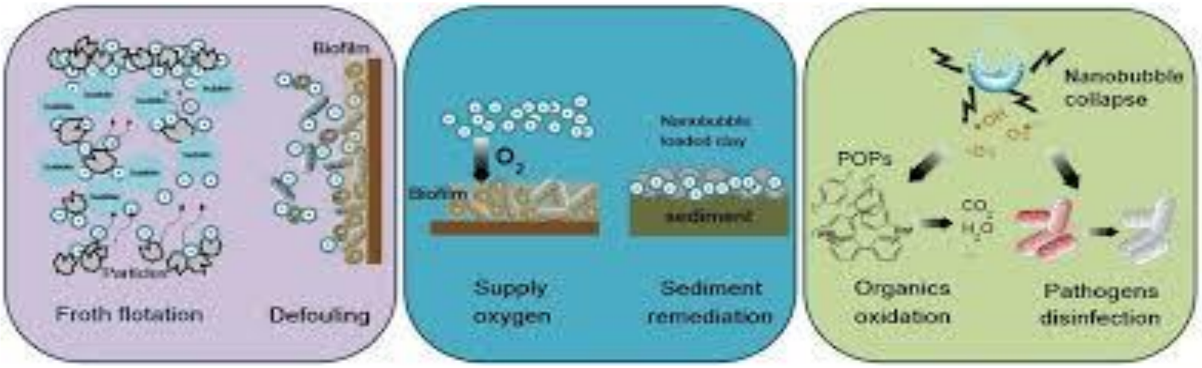

Fig. 5: Environmental and biological applications of nanobubbles in aquaculture systems.

Economic Benefits of Nanobubble Technology

The adoption of nanobubble technology can bring about economic benefits to shrimp farmers. For instance, the increase in oxygen transfer efficiency can reduce the amount of energy used in the aeration system, which can lower the cost of operations in aquaculture farms (Mauladani et al., 2020). Also, the increase in growth performance of shrimp can bring about higher harvest returns to shrimp farmers (Choi et al., 2021). Studies on the economic feasibility of using nanobubble technology in shrimp farming have shown that, although there are investment costs in using the nanobubble system, the long-term benefits of using the system can make it economically feasible for shrimp farming (Mauladani et al., 2020).

Environmental Sustainability

Aquaculture is also benefitting from enhanced environmental sustainability through the use of nanobubble technology. It does this by increasing the oxygen levels in water and also stimulating microbial activity, both of which can help to minimize organic waste build-up and nutrient pollution in shrimp ponds (Wang and collaborators, 2023).

The use of nanobubbles enhances the rate of microbial breakdown of organic materials in water, which will help to lower the amount of harmful gases released into the water, like ammonia and/or hydrogen sulfide, that can adversely affect aquatic-based ecosystems (Zhou and collaborators, 2022).Finally, the use of nanobubbles will also improve the overall wastewater treatment capabilities (efficiency) for aquaculture companies, which will help minimize their environmental impacts and also promote more responsible, sustainable water management (Yaparatne 2024).

Challenges and Limitations of Nanobubble Technology

One major limitation is the relatively high initial cost associated with nanobubble generation equipment compared to conventional aeration systems (Mauladani et al., 2020). Another obstacle is the absence of standard operating procedures for aquaculture applications using nanobubble systems. Recommendations for optimal operating conditions, including bubble size, gas type, and aeration time, are likely to differ based on aquaculture production conditions (Sravani et al., 2024). Finally, more large-scale field studies are required to further assess the effectiveness and long-term environmental consequences of applying nanobubble technology in commercial aquaculture settings (Garcia-Segura et al., 2023). However, ongoing advancements in technology as well as research into enhancing the cost and/or performance of nanobubble systems will facilitate their use over time.

Conclusion

Nanobubble technology is an innovative tool with vast potential to increase the productivity, efficiency, and sustainability of modern shrimp aquaculture systems. Moreover, nanobubble technology is equipped with strong antimicrobial properties, particularly with ozone nanobubbles, which can control the growth of pathogenic microorganisms, thus reducing disease outbreaks in shrimp aquaculture. Nanobubble technology can also contribute to sustainable aquaculture by reducing the accumulation of organic waste, increasing wastewater treatment efficiency, and minimizing the use of antibiotics and chemicals in aquaculture. Moreover, economic evaluations of nanobubble technology have shown that it can increase the profitability of aquaculture farms by increasing harvest productivity and reducing costs in the long term. One major limitation is the relatively high initial cost associated with nanobubble generation equipment compared to conventional aeration systems (Mauladani et al., 2020). Another obstacle is the absence of standard operating procedures for aquaculture applications using nanobubble systems. Recommendations for optimal operating conditions, including bubble size, gas type, and aeration time, are likely to differ based on aquaculture production conditions. Finally, more large-scale field studies are required to further assess the effectiveness and long-term environmental consequences of applying nanobubble technology in commercial aquaculture settings. However, ongoing advancements in technology as well as research into enhancing the cost and/or performance of nanobubble systems will facilitate their use over time.

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