

Application Of Nanobubble Technology In Wastewater Treatment For Enhanced Pollutant Removal: A Comprehensive Review

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Abstract — Keeping global water resources clean is becoming harder every year. Industrial growth has pushed wastewater systems into a corner, and the usual treatment methods are starting to look worn out. They demand a lot of energy and still struggle with stubborn pollutants that refuse to break down. This review takes a close look at nanobubble (NB) technology as a more sustainable option. Nanobubbles are tiny, sub-micron gas cavities with an unusually long life in water, and that alone makes them interesting. They also bring unusual physicochemical properties, including high internal pressure and the formation of reactive oxygen species (ROS). The paper covers the basic mechanisms behind NBs, their contribution to aeration and flotation, and their strong performance in removing organic dyes, nutrients, heavy metals, and pathogens. Reported studies show that NB-based systems can push Chemical Oxygen Demand (COD) removal above 90% while using much less energy than conventional activated sludge treatment. The aim here is straightforward: give researchers and practitioners a clear view of the technical value and economic promise of NB technology in modern water purification.

Keywords — Nanobubble technology, advanced oxidation, wastewater treatment, aeration efficiency, pollutant removal, sustainable engineering.

I. INTRODUCTION

1.1. The Crisis of Conventional Wastewater Management

The preservation of water resources has become a critical global priority as population growth and industrial expansion intensify the discharge of diverse pollutants into the environment. Traditional wastewater treatment technologies, primarily centered around biological activated sludge processes and conventional chemical oxidation, are increasingly struggling to meet stringent regulatory standards (Atkinson et al., 2019; Sakr et al., 2021). A major limitation of these systems is their inability to efficiently remove recalcitrant organic pollutants, such as pharmaceuticals, pesticides, and complex industrial dyes, as well as high concentrations of nutrients and heavy metals (Kaskote et al., 2024; Wu et al., 2021). Furthermore, the aeration stage in traditional activated sludge systems is highly energy-intensive, often accounting for 50% to 75% of a wastewater treatment plant's total electricity consumption, which significantly drives up operational costs (Kaskote et al., 2024).

1.2. The Advent of Nanobubble Technology

To address these technical and economic challenges, nanobubble technology has emerged as a promising, environmentally friendly alternative. Nanobubbles are gas-filled cavities in an aqueous medium with diameters typically less than 200 nm, although they are operationally defined in broader contexts as being under 1000 nm (Atkinson et al., 2019; Kaskote et al., 2024).

Unlike conventional macrobubbles, which rise and burst almost immediately due to buoyancy, NBs exhibit unique physicochemical properties—including extreme longevity, high internal pressure, and the generation of reactive oxygen species—that facilitate superior mass transfer and pollutant degradation (Jia et al., 2023; Sakr et al., 2021). This review explores the fundamental mechanisms of NBs and their specific applications in flotation, aeration, and advanced oxidation for the removal of a wide array of contaminants.

II. FUNDAMENTAL PHYSICOCHEMICAL PROPERTIES OF NANOBUZZLES

The efficacy of NB technology in wastewater treatment is governed by three primary physical phenomena that differentiate them from larger gas bubbles.

2.1. Extraordinary Longevity and Stability

Conventional bubbles exhibit a rapid rise velocity governed by buoyancy, leading to short residence times in the water column. In contrast, NBs possess a virtual disappearance of buoyancy (Sakr et al., 2021). Their small mass and size allow them to be dominated by Brownian motion rather than gravitational or buoyant forces, keeping them suspended in the liquid phase for weeks or even months (Soyluoglu et al., 2023; Wu et al., 2022). Research indicates that NBs with radii in the range of 150–200 nm are exceptionally stable, a characteristic that provides a sustained gas-liquid

interface for chemical reactions and biological support (Sakr et al., 2021).

2.2. High Specific Surface Area and Gas Dissolution

The specific surface area of a gas bubble is inversely proportional to its diameter ($A/V = 3/r$). As bubble size moves from the macro-scale to the nano-scale, the total surface area available for mass transfer increases exponentially for the same volume of gas (Sakr et al., 2021; Tekile et al., 2017). This characteristic significantly improves the gas dissolution rate. For instance, MB and NB aeration has been shown to improve the mass transfer of oxygen or ozone at the water-gas interface far more effectively than traditional aeration, achieving higher dissolved oxygen levels which are crucial for aerobic biodegradation (Jia et al., 2023; Sakr et al., 2021).

2.3. Surface Charge and Internal Pressure

Nanobubbles typically carry a negative surface charge (zeta potential), which induces electrostatic repulsion between individual bubbles and prevents coalescence into larger, less stable bubbles (Hutagalung et al., 2023; Wu et al., 2021). Furthermore, the internal pressure of a nanobubble is governed by the Young-Laplace equation ($P=P_0 + 2\gamma/r$), where r is the radius. As r decreases to the nano-scale, the internal pressure increases dramatically, which further promotes the dissolution of the contained gas into the surrounding liquid (Sakr et al., 2021; Tekile et al., 2017).

III. MECHANISMS OF ENHANCED POLLUTANT REMOVAL

Nanobubbles contribute to wastewater purification through three distinct technical pathways: aeration, flotation, and advanced oxidation.

3.1. Enhanced Aeration and Biological Support

In biological wastewater treatment, the concentration of dissolved oxygen is a limiting factor for the growth of aerobic heterotrophic microorganisms (Sakr et al., 2021). Insufficient oxygen can disrupt biological processes or encourage unwanted anaerobic growth. NB technology efficiently increases the DO content and oxygen mass transfer rate, accelerating the removal of pollutants like ammonia and organic carbon (Sakr et al., 2021). Studies have confirmed that removal rates for Total Nitrogen and Total Phosphorus were 7.5% and 6% higher, respectively, when using MB/NB aeration compared to traditional bottom aeration (Sakr et al., 2021).

3.2. Improved Flotation Processes

Dissolved air flotation is commonly used to separate suspended solids and fats. Small-sized bubbles enhance this process by attaching more effectively to fine particulates. In specific industrial applications, such as poultry slaughterhouse wastewater treatment, NBs used in flotation have achieved up to 95% removal of Chemical Oxygen Demand (Kaskote et al., 2024).

3.3. Generation of Reactive Oxygen Species

One of the most valuable aspects of NB technology is its ability to generate free radicals, particularly hydroxyl radicals (OH), upon the shrinkage or collapse of the bubbles (Sakr et al., 2021; Wang et al., 2025). These radicals are highly non-selective and powerful oxidants capable of breaking down complex organic molecules that are resistant to standard treatment (Atkinson et al., 2019). For example, the use of oxygen NBs in advanced oxidation has achieved up to 92.5% COD removal in complex waste streams (Kaskote et al., 2024).

IV. PERFORMANCE IN SPECIFIC POLLUTANT REMOVAL

4.1. Organic Contaminants and Recalcitrant Dyes

NB-based systems have shown high efficiency in degrading persistent organic pollutants. A meta-analysis of removal rates reveals several key successes:

- **Rit Dye:** Air NBs alone or combined with ultrasonic/H₂O₂ treatment achieved 90% removal through surface charge attraction and OH generation (Wu et al., 2021).
- **Oxytetracycline:** Oxygen NBs coupled with photodegradation reached 98% removal (Wu et al., 2021).
- **1,4-Dioxane:** Ozone NBs demonstrated a 98.5% removal rate (Wu et al., 2021).
- **Sodium Dodecyl Benzene Sulfonate:** Oxygen NBs in a vacuum ultraviolet system reached 99.8% removal efficiency (Wu et al., 2021).

4.2. Nutrient and Ammonia Removal

Ammonia ($NH_3 - N$) removal is significantly enhanced by NB technology. In municipal sewage studies, the concentration of ammonia-nitrogen was reduced by >15% more than with traditional aeration methods (Sakr et al., 2021). The efficient utilization of oxygen via MB/NB aeration can reach nearly 100% under optimum conditions, ensuring the rapid nitrification of ammonia (Sakr et al., 2021).

4.3. Heavy Metals and Inorganics

NB technology is effective as a pretreatment method for inorganic contaminants. In one study, aluminum

concentrations were reduced from 14.9 to 1.176 mg/L, and lead concentrations decreased from 4.227 to 0.065 mg/L (Sakr et al., 2021). Additionally, fluoride removal reached 76.7% when NBs were combined with specific polymers, an increase of 7.1% over traditional treatment methods (Sakr et al., 2021).

4.4. Pathogen Deactivation

NBs serve as an efficient disinfection agent. In domestic wastewater treatment, NB disinfection reduced Biochemical Oxygen Demand from 342 to 10 mg/L and COD from 704 to 35 mg/L (Sakr et al., 2021). Most notably, it achieved a 99.96% reduction in total coliforms and a 99.92% reduction in fecal coliforms (Sakr et al., 2021). This high level of deactivation is attributed to the synergistic effect of high DO levels and ROS-mediated cell wall disruption (Atkinson et al., 2019).

V. GENERATION METHODOLOGIES FOR NANOBUBBLES

The method of generation determines the concentration, size, and stability of the NBs.

- **Hydrodynamic Cavitation:** This involves passing a liquid-gas mixture through a venturi nozzle or orifice, creating pressure drops that induce cavitation and bubble formation (Kaskote et al., 2024; Verinda, 2024).
- **Pressurized Dissolution:** Gas is dissolved into a liquid at high pressure and then released through a nozzle, causing the supersaturated gas to precipitate as NBs (Wu et al., 2022).
- **Fluidic Oscillators:** Recent advancements have explored low-energy generation through fluidic oscillators, which can produce micro- and nanobubbles with minimal power input compared to traditional pumps (Kaskote et al., 2024; Pandhal et al., 2018).

VI. ECONOMIC AND ENVIRONMENTAL ASSESSMENT

6.1. Energy Efficiency and Cost Reduction

The primary economic benefit of NB technology is the reduction in energy consumption for aeration. By achieving higher oxygen transfer efficiencies, plants can significantly lower the electricity required to maintain aerobic conditions (Kaskote et al., 2024). Furthermore, the reduction in sludge volume often associated with small-sized bubble aeration leads to lower handling and disposal costs (Sakr et al., 2021).

6.2. Decentralized Treatment and "Green" Alternatives

NB technology offers a chemical-free alternative to traditional oxidants like chlorine, which are dangerous to handle and produce harmful disinfection byproducts (Atkinson et al., 2019). Because of their low chemical requirements, NB technologies could be distributed throughout decentralized water treatment systems in both developed and developing countries, supporting the United Nations' goal of access to safe water (Atkinson et al., 2019).

VII. CHALLENGES AND FUTURE DIRECTIONS

Despite the clear advantages, several gaps remain in the implementation of NB technology:

1. **Characterization in Complex Matrices:** There is a critical need for techniques that can measure NB size and surface properties in complex wastewater containing high concentrations of salts, organics, and colloids (Atkinson et al., 2019; You et al., 2025).
2. **Mechanistic Understanding:** The physical and biochemical interactions between NBs and microbial communities in aerobic treatment and anaerobic digestion are still not fully understood (Zhou et al., 2022).
3. **Scalability:** While lab and pilot-scale studies are abundant, engineering limitations regarding the versatility and scalability of NB generators in full-scale municipal plants remain a hurdle (Jia et al., 2023; Zhou et al., 2022).

VIII. CONCLUSION

Nanobubble technology represents a significant leap forward in wastewater treatment. By leveraging the unique stability, massive surface area, and radical-generating capabilities of NBs, researchers have demonstrated removal efficiencies for COD and other pollutants exceeding 90% across various applications (Kaskote et al., 2024; Wu et al., 2021). The technology not only enhances the removal of recalcitrant organics, nutrients, and heavy metals but also offers a pathway to reduce the energy-intensive nature of traditional aeration systems. As characterization methods and generation techniques continue to evolve, NB technology is poised to become a cornerstone of sustainable, decentralized, and high-efficiency water purification systems worldwide.

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