Nanobubble Technology in Environmental Engineering: Revolutionization Potential & Challenges

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Nanobubbles (NBs) are defined as bubbles with diameters less than 1000 nm. The concept of NBs was first proposed in 1994 to explain the underpredicted attractive forces observed between hydrophobic surfaces in water[1]. However, the existence of NBs cannot be explained by the classic Laplace Pressure Bubble Catastrophe theory, and therefore, the existence of these NBs has remained a topic of debate for several years. The existence of NBs started to gain gradual acceptance in 2000, when the first image of such nano-scale bubbles was obtained through atomic force microscopy. Since then, significant research attention has been devoted to the fundamental characterization of NBs, including their generation process and physico-chemical surface properties [2]. In 2003, a sonication method for the formation of NBs in solution (bulk NBs) was developed, which subsequently facilitated the implementation of the bulk NBs in biomedical research and applications, such as drug delivery [3].

Apart from their unique size property, NBs also differ from other types of bubbles in terms of their longevity, negative surface charge, low buoyancy, high gas solubility, and capability to generate free radicals. Owing to these characteristics, NBs have been progressively used in addressing environmental issues since 2004. Various lab-scale studies have been performed to test their potential for mineral froth flotation, membrane defouling, water disinfection, and sediment remediation (Fig. 1). Recently, a few studies have evaluated the possibility of scaleing-up and application of NBs to an industrial level. We believe that the successful integration of NB technology into environmental engineering can lead to a technological revolution by significantly improving the efficiency of contaminant removal, downsizing treatment facilities, and reducing operation times and costs. However, the current knowledge of how the above-mentioned NBs properties exsit when applied in environemtal engineering is not yet widespred. The influence on the generation and stability of NBs due to complex water composition on applied engineering is still unclear. Therefore, it is necessary to re-evaluate the application of NBs in environmental engineering, particularly targeting the technological revolution potential and challenges.

(1) High gas transfer efficiency

In natural water restoration and wastewater treatment, aeration plays a major role in delivering oxygen that is important not only as a life-sustaining component for aquatic life, but also as the biochemical reaction substrate for oxidative pollutant degradation.

Although the operating of conventional mechanical aerators or diffusers requires large amounts of electrical energy, which accounts for 45-75% the total operational cost of wastewater treatment plants, the oxygen transfer efficiency is limited to 6-10%. NBs have low buoyancy, and can therefore slowly diffuse oxygen into the surrounding water. Recent results have shown that the oxygen utilization rate and the volumetric mass transfer coefficient in NB-aerated synthetic wastewater treatment systems can be double of conventional bubble aerated systems. The degradation of organic matter using NBs also requires less than half the retention time that is conventionally required. Furthermore, our recent study on lake sediment restoration showed that supplying oxygen-filled NB-modified clay material to the anoxic lake sediment can maintain dissolved oxygen at the level of >6 mg/L for over 6 months[4]. Thus, the higher gas transfer efficiency makes NB aeration a cost-effective oxygen supply approach. However, it should be noted that the Brownian motion of NBs and high levels of heat and shock waves generated from NB collapse may induce stress or cause damage to biological cells and dislodge biofilms.

(2) Oxidation of organics and pathogens disinfection

Oxidation of persistent organic pollutants (POPs), such as polychlorinated biphenyls and phenolic halogenated compounds, and disinfection of pathogens are important for upgrading the performance of treating drinking water and wastewater. NB technology can offer a cost-effective non-reagent approach that generates numerous reactive oxygen species (ROSs), including hydroxyl radicals (·OH), superoxide anion radicals ($O_2\cdot^-$), and singlet oxygen ($^1O_2$), during the process of NB collapse. Although promising results have been reported on the removal of POPs and deactivation of different enteric pathogens, the ROSs generated from NBs were mostly characterized in ultrapure water. The effectiveness of the generated ROSs under the influence of various types of wastewater with complex compositions is yet to be evaluated.

(3) Generation in raw wastewater

The main focus of the NB technology lies in the cheap and stable generation of NBs in wastewater, which holds high potential for practical applications. Currently, hydrodynamic cavitation through spiral liquid flow or venture tubes is thought to be the most energy-efficient method. However, this method is inappropriate and inefficient for raw wastewater that contains particulate matter, as the particulates man hinder the formation of the NBs, and may even destroy the generator completely. Fluidic oscillators can facilitate NB formation in wastewater, but the cost involved prohibits scaling up to industry, because it requires extending the currently used fluidic oscillator regime to several tens of kHz[5]. The generation of micro-bubbles is much cheaper than NBs due to the lower requirements of the bubble generator. Several studies have demonstrated that the beneficial effects of the micro bubbles are similar to those of NBs. Therefore, it may not be practical to rely exclusively on NBs, a mixture of micro-bubbles and NBs may reduce the operational cost to a certain extent and make the practical implementation of this approach feasible.

In summary, the mechanisms and efficacy of applying NB technology to water pollution control have been only partially revealed. Further investigation is required to understand the interactions of NBs with functional microbial communities, particularly with regard to the the process of NB collapse. Moreover, scaling up of generating NBs in raw wastewater treatment systems remains a challenge. Nonetheless, we believe that efforts to tackle these challenges will enable the NBs technology to offer revolutionary solutions to pollution issues in environmental engineering, as a “green” nanotechnology that does not generate secondary hazards.

Declaration

The authors declare no competing financial interest.

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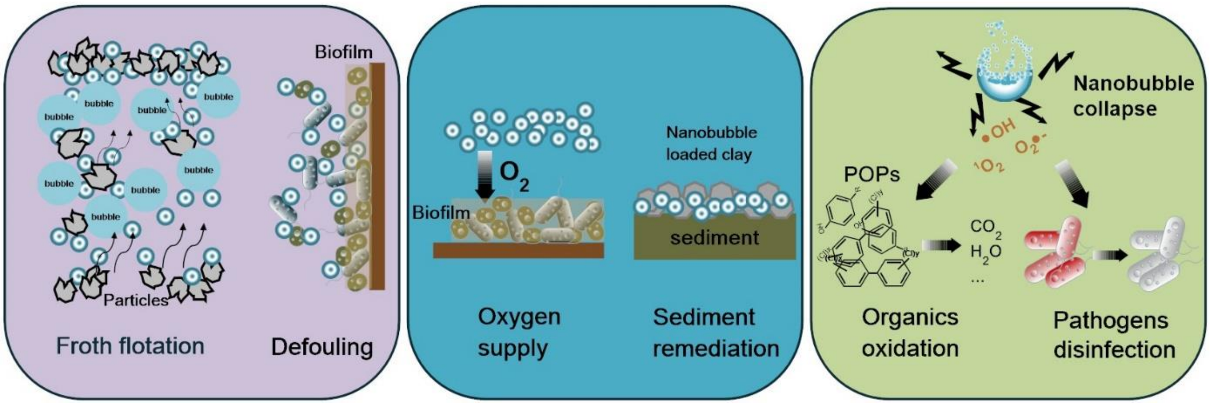

Fig.1 Potential contributions of nanobubble technology on environmental engineering due to their unique physical, biological and chemical characteristics.