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Leveraging Nanobubbles to Improve Mass Transfer Efficiency in Bioprocesses

Shige Hisa*

Department of Biochemistry, Federal University of Santa Catarina, Florianópolis 88040-900, SC, Brazil

Introduction

Bioprocesses are critical to numerous industries, including pharmaceuticals, agriculture, food production and environmental management. A key factor influencing the efficiency of these processes is effective mass transfer, particularly for gases such as oxygen and carbon dioxide, which are essential for the growth of microorganisms and cell cultures. Traditionally, techniques such as mechanical agitation, sparging and membrane systems have been employed to achieve mass transfer. However, these conventional methods often face challenges, including high energy consumption, shear stress on sensitive biological systems and limitations in gas solubility and distribution. Nanobubbles, ultra-fine gas bubbles with diameters typically less than 200 nanometers, offer a promising alternative to enhance mass transfer. Their distinctive properties such as a high surface area-to-volume ratio, prolonged stability in liquids and resistance to coalescence enable significant improvements in gas solubility and distribution. This article delves into the potential of nanobubbles to optimize mass transfer in bioprocesses, exploring their unique properties, mechanisms and applications across various biotechnological domains [1,2].

Description

Unlike larger bubbles, which quickly ascend to the surface and burst, nanobubbles demonstrate exceptional stability in liquids. This stability stems from their high Laplace pressure, which is inversely related to the bubble radius, allowing nanobubbles to remain suspended for extended periods and provide continuous gas transfer. Their small size gives nanobubbles a high surface area-to-volume ratio, which enhances the efficiency of gas exchange between the bubble and the surrounding liquid, making them particularly effective in increasing gas solubility, such as oxygen in aqueous solutions. Nanobubbles experience minimal buoyancy forces due to their tiny size, which enables a more uniform distribution throughout the liquid medium. This even distribution ensures that gases are supplied consistently across the entire bioreactor, promoting uniform growth of microorganisms or cultured cells. Additionally, nanobubbles often carry a negative surface charge, which prevents them from merging into larger bubbles and enhances their electrostatic stability, further prolonging their effectiveness in mass transfer applications.

The high surface area-to-volume ratio of nanobubbles creates a greater gas-liquid interface, significantly improving the solubility of gases. This is particularly advantageous in oxygen-limited bioprocesses, where increased oxygen availability can lead to enhanced cell growth and productivity. Moreover, nanobubbles dissolve more rapidly than larger bubbles, providing a more immediate and effective transfer of gases into the liquid phase, which supports the metabolic needs of microorganisms or cultured cells. Traditional gas transfer methods often encounter limitations due to mass transfer resistance at the gas-liquid interface. Nanobubbles address this challenge by reducing resistance through their high surface area and uniform distribution, facilitating more efficient gas exchange. Additionally, the presence of nanobubbles can induce micro-convection currents within the liquid medium, further enhancing gas mixing and distribution and improving overall mass transfer rates [3-5].

Conclusion

Nanobubbles are emerging as a groundbreaking technology with the potential to revolutionize mass transfer in a variety of bioprocessing applications. Their distinctive characteristics, including exceptional stability, a high surface area-to-volume ratio and minimal buoyancy, make them particularly effective in enhancing gas solubility and distribution within liquid media. Whether applied to microbial fermentation, cell culture, wastewater treatment, or bioremediation, nanobubbles have shown the ability to significantly improve process efficiency and productivity. Despite these promising benefits, ongoing research and development are essential to address technical challenges, optimize operational parameters and ensure the safe and effective integration of nanobubbles into existing systems. As advancements continue, nanobubbles are set to play a pivotal role in shaping the future of bioprocessing, fostering innovation and sustainability across various industries.

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Conflict of Interest

There is no conflict of interest by author.

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***Address for Correspondence:** Shige Hisa, Department of Biochemistry, Federal University of Santa Catarina, Florianópolis 88040-900, SC, Brazil; E-mail: shisa@hmail.com*

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