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# Modeling bubble dynamics and radical kinetics in ultrasound induced microalgal cell disruption

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ABSTRACT

Microalgal cell disruption induced by acoustic cavitation was simulated through solving the bubble dynamics in an acoustical field and their radial kinetics (chemical kinetics of radical species) occurring in the bubble during its oscillation, as well as calculating the bubble wall pressure at the collapse point. Modeling results indicated that increasing ultrasonic intensity led to a substantial increase in the number of bubbles formed during acoustic cavitation, however, the pressure generated when the bubbles collapsed decreased. Therefore, cumulative collapse pressure (CCP) of bubbles was used to quantify acoustic disruption of a freshwater alga, *Scenedesmus dimorphus*, and a marine alga, *Nannochloropsis oculata* and compare with experimental results. The strong correlations between CCP and the intracellular lipid fluorescence density, chlorophyll-a fluorescence density, and cell particle/debris concentration were found, which suggests that the developed models could accurately predict acoustic cell disruption, and can be utilized in the scale up and optimization of the process.



## 1. Introduction

Acoustic cavitation, as the basis of many applications of ultrasound in the high frequency range (from 20 kHz to 10 MHz), usually involves the formation, growth, oscillation, and powerful collapse of bubbles or cavities. Because the event of bubble collapse occurs in small intervals of time (milliseconds) and releases large magnitudes of energy over a very small space, a significant increase in temperature (up to several thousand degrees Kelvin) and pressure (several hundred atmospheres locally) is obtained [1–4]. The extremely high temperatures and pressures formed in collapsing bubbles in aqueous solutions are capable of decomposing water vapor into highly reactive radicals such as $H^{\cdot}$ and $^{\cdot}OH$ [5,6]. Redox reactions initiated by these radicals have been found to weaken the composition of microbial cell walls such as glycoproteins and polysaccharides to the point of disintegration [5,7]. In addition, intense shock waves and shear forces produced by the bubble collapse are known to break down biological cell walls and membranes, wash out cell contents, and reduce particle sizes of vegetal materials [8–10].

The vast majority applications of acoustic cavitation are in wastewater treatment [11–13], textile processing [14], crystallization [15], and biological processing [2]. Acoustic cavitation has also been reported to effectively decrease the growth rate of algae, inhibit cell division, or cause immediate damage on photosynthetic activities of algae, as well as physically breaking the cell wall/membrane. For example, Lee et al. [16] found that under high power ultrasound, acoustic cavitation could directly rupture whole cells or gas vacuoles within the cells. TEM evidence has shown this effect on a single *Microcystis aeruginosa* cell following ultrasonic treatment at 28 kHz for 30 s (intensity of 0.12 W/cm$^3$). In a similar study using acoustic cavitation to inhibit the growth of irradiated algal cells, *Spirulina (Arthrospira) platensis*, Tang et al. [17,18] concluded that the growth rate of algal cells was reduced to 38.9% of the control in 5-min treatment due to changes in the functionality and integrity of cellular and subcellular structures. Zhang et al. [19] found that 5 min exposure of *M. aeruginosa* to 25 kHz ultrasound (intensity of 0.32 W/cm$^3$) caused algae sedimentation and reduced the photosynthetic activity of algae population. In addition, some researchers have used acoustic energy for microalgal cell disruption and lipid extraction. For example, solvent-free ultrasound-assisted extraction significantly improved oil recovery of *Nannochloropsis oculata* compared with conventional extraction methods (Bligh and Dyer) [20]. Wang et al. [9] found that high frequency focused ultrasound and combination of high and low frequency ultrasounds were effective in microalgal cell disruption.

Some research has been conducted to understand the bubble dynamics in acoustical field and their radical kinetics. For example, Gogate and Pandit [21] described the motion of a single bubble by

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