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Research Paper

Effect of Sonication Frequency and Power Intensity on the Disruption of Algal Cells: Under Vacuum and Non-Vacuum Conditions

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Abstract

The presence of algae caused by anthropogenic eutrophication in water has become a severe environmental issue. Various treatment options for algae removal have been developed, such as filtration, coagulation, sedimentation, flotation, algicides, ozone, and photolysis. However, these technologies are complex, expensive, consume considerable amounts of various chemicals, and may cause further pollution (i.e., by-product formation). Ultrasonic exposure is an alternative method for removing algae from water that is environmentally friendly (i.e., no addition of chemicals) and almost unaffected by any turbidity in the water. In this study, process optimization of ultrasonication (e.g., by adjusting frequency, power intensity, and exposure time) for the removal of alga was tested under vacuum and non-vacuum conditions. Experiments were conducted on a batch of algae solution in a clear glass tube ultrasonicated by a 20 kHz transducer for 180 minutes. The tube was depressurized to -67 N/m^2 in a depressurizing chamber. The data was collected at transducer depths of 0.06, 0.13, and 0.19 m. It was concluded that the optimum condition (i.e., 92% algal cell disruption) was achieved when the power intensity was 7 kWh/m^3, under vacuum conditions, at a frequency of 20 kHz and 180 minutes of exposure time. Higher power intensity gave higher energy for cell disruption, moreover by depressurizing the air above the algae solution, the lysis effect for algae reduction increased from 20% to 70% compared to the non-depressurized system due to higher cavitation bubble production. In addition, the depth of the transducer was another factor that could increase the lysis of the algae water. Therefore, this technology has future potential application for algae removal from water.

Keywords: *algae; cavitation; depressurized; ultrasonication; water treatment.*

Introduction

Algae blooms are increasing both in magnitude and frequency worldwide and pose serious environmental risks to freshwater systems ranging from aesthetic to serious human health risks (i.e., toxins produced by algae may cause skin irritation, fever, and liver damage) [1]. Consequently, the removal of this organism by using water treatment technology is necessary. On the other hand, algae can also be an economical issue in water treatment facilities because it can clog filters, which leads to the use of a significant amount of chemicals, frequent backwashing (i.e., reducing the production of water), and deterioration of water quality [2]. In addition, several advanced water treatment processes have been proposed to improve the removal of algae. Advanced oxidation processes (e.g., ozone and photocatalysis) can reach high removal efficiencies; however, they may further pollute the treated water due to by-product formation. Moreover, these technologies are complex, expensive, and consume considerable amounts of various chemicals [3]. Developing an alternative water treatment technology is urgently needed to overcome this problem.

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In recent decades, ultrasonic exposure has become an alternative method for removing algae from water [4]. This treatment is relatively environmentally friendly compared to other techniques (e.g., coagulation, sedimentation, algicides, ozone, etc.) because it does not involve any chemicals and is almost unaffected by any turbidity in the water [1]. The performance of ultrasonication is based on the formation and collapse of bubbles during the cavitation process in the water. It has been reported that the overall effects of acoustic cavitation during ultrasonication can be summarized as follows [5]: 1) high-power low-frequency ultrasound results in the rupturing of bubble cavitation, which directly shears algae cells; 2) low-power ultrasound can induce a declumping effect that breaks algae aggregates into single cells; and 3) higher frequency ultrasound can generate more free radicals (OH*), which reduce cell numbers via chemical attack. Power density (W/m^3), frequency (kHz), and exposure time (min) of ultrasonic irradiation are considered essential operating parameters. Several studies at laboratory scale (i.e., reactor volume <2 L) observed the removal of algae with longer duration and higher frequency of ultrasonication, and more significant power density resulted in better algae removal [6–8].

Ultrasonication of *Microcyctis aeruginosa* has indicated that a higher frequency will not always produce a higher removal efficiency (i.e., the order of efficiency for alga reduction was 20 < 1146 < 864 < 580 kHz) [6]. Moreover, the removal of algal cells increases with the increase in ultrasound power and exposure time due to higher energy input to break algae cells [7]. However, higher frequencies, higher power, and longer durations of ultrasonic irradiation require more electric power (i.e., higher operational costs). Moreover, most studies are limited to a small laboratory scale (i.e., reactor volume <2 L), and there is limited information regarding process optimization (power density, frequency, and exposure time) in the scale-up of the technology (reactor volume >500 L) [9]. Therefore, process optimization under a large reactor system is urgently needed to support this technology's field-scale application.

This study tried to optimize the process parameters (power density, frequency, and ultrasonication radiation) at a relatively small test volume (>500 mL). In addition, for the first time, algae removal by ultrasound irradiation was investigated under vacuum and non-vacuum conditions (i.e., a combination of ultrasound and pressure homogenization) to achieve higher cell removal with lower energy consumption. The systematic analysis of ultrasound applications will provide insight into the field application of ultrasonic irradiation for algae removal.

Materials and Method

Reactor set-up

The research was conducted on a laboratory scale and used artificial raw water. A reactor with a volume of around 2,000 mL was used to determine the effect of sonification frequency, power, and duration of exposure on algae removal (Figure 1).

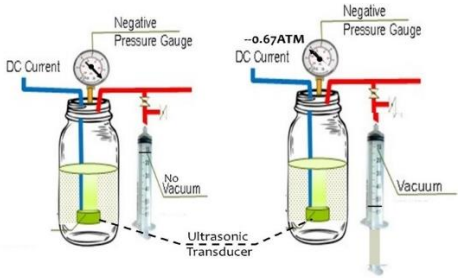

Figure 1 The ultrasonication reactors with a volume of 2000 mL. The height of the water was varied based on the water volume (6 cm, 12.5 cm, and 19.1 cm) and the ultrasonic transducer was placed around 2-5 cm from the bottom of the glass.

Table 1 shows the characteristics of the artificial raw water used in this study. Seeds of Chlorophyta-chlorella sp. were obtained from the 'Pakan Alami' algae nursery laboratory in Bekasi, Indonesia. The algae concentration was set at 6 x 10^5 cells/mL as the initial concentration in monoculture for the experiment. The ultrasonication experiments were carried out with relatively low power intensity (2.56 to 7.68 watts/L) and low frequency (20 kHz) to support process optimization for the practical application of ultrasound [9].

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The total water samples used in this study varied from 500 mL to 1500 mL (i.e., different water heights) to check the effectiveness of the ultrasonication probe. Moreover, the ultrasonication experiments were done under vacuum conditions (-67 N/m^2) as well as non-vacuum conditions (0 N/m^2). Sonication times were 0, 30, 60, 120, and 180 minutes. Samples were collected for each sonication time, followed by a direct count of algae cells using a microscope (i.e., quadrant method analysis) to quantify the algae cells.

Table 1 Characteristics of artificial water.

Parameters	Units	Concentrations
Biochemical Oxygen Demand (BOD)	mg/L	50
Total N	mg/L	20
Total P	mg/L	4
Chlorophyta-chlorella sp.	cell/mL	6×10^5

The experiment was carried out under vacuum and non-vacuum conditions in a reactor with a volume of 2,000 mL. Water volume and power intensity were varied at the same frequency, as shown in Table 2.

Table 2 Variation of power intensity, frequency, and water level during experiments.

Batch Condition	Water Volume (mL)	Power Intensity (kW/m^3)	Frequency (kHz)	Water Level (m)
Vacuum	500	7.68 ; 3.84 ; 2.56	20	0.0625
	1,000	7.68 ; 3.84 ; 2.56		0.125
	1,500	7.68 ; 3.84 ; 2.56		0.191
Non Vacuum	500	7.68 ; 3.84 ; 2.56	20	0.0625
	1,000	7.68 ; 3.84 ; 2.56		0.127
	1,500	7.68 ; 3.84 ; 2.56		0.191

Data Collection Method

Data collection was done by direct observation in the lab. Algae, the object of research, were exposed to ultrasound vibrations. The reference level for the algae concentration was determined by counting the number of intact algal cells after a sample was taken from a reactor. Observations were made using an LCD microscope (Nanyang Srate Optical Instrument, TXS11-02C-LCD) that could be observed and stored in soft copy. The calculation of the number of algae was carried out in a counting chamber.

The procedure for calculating the concentration followed the improved Neubauer counting chamber calculation procedure. The ultrasound's intensity was measured by measuring the power delivered by the transducer divided by the volume of raw water containing algae. Ultrasonication was carried out with 1, 2 and 4 transducers with a current of 0.08 A at 24 volts DC, respectively. Thus, the amount of power delivered to the water during the treatment was 2.56, 3.84, and 7.68 watt/L. Table 3 shows the definition of some of the parameters during the experiment. The height of the water above the transducer was calculated based on the volume of water in the vessel divided by the cross-sectional area of the vessel minus the height of the transducer by 1.5 cm.

Table 3 Parameters observed throughout the experiment.

Parameter	Description	Unit
Number of cells	The number of algal cells is expressed as the number of cells per liter Cells/L	Cell/L
	Percentage of cells after ultrasonication	Ct/Co
Power intensity	Power consumed by the transducer	watt/L
Height of water	The volume of water in the vessel divided by the cross-sectional area of the vessel minus the height of the transducer (1.5 cm)	meter
Level of negative pressure	Vacuum pressure is expressed in terms of air pressure difference from the ambient air pressure	N/m^2

The negative vacuum pressure was measured using a vacuum manometer. The vacuum pressure was observed at a constant level throughout the experiment. The unit used as a measurement reference was bar converted to pascal (N/m^2).

Measurement of Algae Concentration

Measurement for the algae counting was carried out by direct counting using a microscope (Nanyang Srate Optical Instrument, TXS11-02C-LCD). The algae were counted under the microscope at different magnifications, depending on their size. Larger forms were counted under low magnification, while high magnification was used on small forms or those difficult to identify. An immersion lens enabled very small algae to be counted. To ensure good reliability, sparsely occurring larger algae organisms were measured over the entire chamber bottom. When the plankton was dense, only part of the chamber bottom needed to be counted; for example, several diagonal fields would cover any unevenness on the bottom.

The total volume of phytoplankton per liter was calculated from the volume estimates of each species in the sample. Measurements of the algae count were carried out carefully. The mean value was obtained by counting the number of individuals in a random cluster. The algae, which were Chlorophyta colonies generated in the Water Quality Lab, Faculty of Civil and Environmental Engineering (FCEE), ITB, were placed in a constant-light incubator to inactivate the culture. The temperature was set to 28 °C and thelight intensity to 500 lux, which remained constant for 24 hours. The algae were initially cultivated in a prepared monoculture.

Water Sample Analysis

The water sample was observed using a digital microscope. The algae concentration was determined using the algae count method. Other parameters observed were pH, biochemical oxygen demand (BOD), NO_2-N, NO_3-N, PO_4-P, and O_2 level. The measurements were done at two different levels of pressure, i.e., ambient atmospheric pressure and -0.67 atm pressure. The equipment used for measuring was the pH meter SAFESEED, the DO Meter AMT08, and the Maxpure TDS-3. The identification of algae was done using an LBA Digimi 13D microscope. The concentration of NO_3, NH_3, and PO_4 was analyzed using Hanna Instruments (HI) chemical test kit with various serial numbers (e.g., NO_2 analysis using HI3873, NO_3 analysis using HI3874, PO_4 analysis using HI 713-25, and NH_3 analysis using HI 700). The BOD and COD parameters were measured using the Indonesia National Standard/ *Standard Nasional Indonesia* SNI 6989.72:2009 and SNI 6989.2:2009 methods, respectively.

Model Development

To facilitate the interpretation of the data, Eq. 1 [10] was used, which shows the remaining percentage of algae removal during the experiment:

$$\%Remaining = \frac{Ct}{Co}\ x\ 100\% \tag{1}$$

where :

Ct = Algae concentration on t (cell/mL)
Co = Initial algae concentration (cell/mL)

The destruction of algae was quantified using Eq. (2) [11]:

$$\frac{dC}{dt} = K.C = \lfloor F(f, and\ Pow, x, Pa) \rfloor . C \tag{2}$$

where :

C = Concentration (mg/L)
f = Ultrasonic frequency (kHz)
t = Ultrasonication time (minutes)
Pow = Ultrasonication power (Watt)
X = Depth of transducer representing the hydrostatic pressure (m)
Pa = Air pressure above water (Pa or N/m^2)

Eq. (1) was further derived to give Eq. (3):

$$\frac{Ct}{Co} = \mathbf{e}^{-\left(\mathbf{K_1}.\Delta\mathbf{P_{ATM}}.+\mathbf{K_2}.\frac{\sqrt{\rho.c.P_{ow}}}{x}\right).f.t} \tag{3}$$

where:

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Ct/Co = Algae removal
K1, K2 = Coefficient (m^2/N)
ΔP_ATM = Absolute value of air pressure reduction above water (Pa)
ρ = Density (kg/m^3)
c = Sound wave velocity (m/s)
Pow = Ultrasonic power (watt)
X = Depth (m)

Based on previous studies [11-12], it was found that the decrease in algae concentration follows the following pseudo-first order equation:

$$\frac{Ct}{Co} = \mathbf{e}^{-\mathbf{0.0041}.\sqrt{\mathbf{P_{ow}}}\ .\mathbf{f.t}} \quad (4)$$

Results and Discussion

The batch experiment was carried out according to the research framework in Table 2 to see how much algae removal occurred undervariations in the position of the ultrasonic power transducer under two different experimental conditions, namely vacuum and non-vacuum. (see Table 4).

Table 4 Concentration and percentage remaining of algae at variation of transducer position.

Vacuum Pressure (-N/m²)	Water Level (m)	Power kWh/m³	0 minute		60 minute		120 minute		180 minute	
			Cell/mL	%	Cell/mL	%	Cell/mL	%	Cell/mL	%
0	0	7	6.12.E+05	100%	6.18.E+05	101%	3.79.E+05	62%	2.98.E+05	49%
	0	7	6.12.E+05	100%	3.61.E+05	59%	2.65.E+05	43%	2.98.E+05	49%
0	0	3	1.17.E+06	100%	9.64.E+05	83%	7.96.E+05	68%	6.57.E+05	56%
	0	3	1.17.E+06	100%	8.00.E+05	69%	7.40.E+05	63%	5.06.E+05	43%
0	0	2	6.92.E+05	100%	5.92.E+05	86%	5.06.E+05	73%	4.33.E+05	63%
	0	2	6.92.E+05	100%	4.97.E+05	72%	3.54.E+05	51%	4.03.E+05	58%
0	0	7	7.52.E+05	100%	7.67.E+05	102%	5.25.E+05	70%	4.38.E+05	58%
	0	7	7.52.E+05	100%	5.84.E+05	78%	3.73.E+05	50%	4.34.E+05	58%
0	0	3	5.88.E+05	100%	5.06.E+05	86%	4.35.E+05	74%	3.74.E+05	64%
	0	3	5.88.E+05	100%	3.94.E+05	67%	3.74.E+05	64%	3.63.E+05	62%
0	0	2	8.04.E+05	100%	7.37.E+05	92%	6.76.E+05	84%	6.19.E+05	77%
	0	2	8.04.E+05	100%	5.60.E+05	70%	6.76.E+05	84%	5.02.E+05	62%
0	0	7	7.20.E+05	100%	6.78.E+05	94%	6.39.E+05	89%	6.01.E+05	84%
	0	7	7.20.E+05	100%	5.63.E+05	78%	6.19.E+05	86%	5.11.E+05	71%
0	0	3	6.16.E+05	100%	5.93.E+05	96%	5.71.E+05	93%	5.49.E+05	89%
	0	3	6.16.E+05	100%	5.63.E+05	91%	4.39.E+05	71%	5.27.E+05	86%
0	0	2	8.44.E+05	100%	8.74.E+05	104%	7.27.E+05	86%	7.22.E+05	86%
	0	2	8.44.E+05	100%	8.32.E+05	99%	6.92.E+05	82%	6.88.E+05	81%
6	0	7	5.40.E+05	100%	5.56.E+05	103%	1.01.E+05	19%	4.34.E+04	8%
	0	7	5.40.E+05	100%	1.66.E+05	31%	9.26.E+04	17%	4.13.E+04	8%
6	0	3	7.96.E+05	100%	4.28.E+05	54%	2.30.E+05	29%	1.23.E+05	16%
	0	3	7.96.E+05	100%	2.18.E+05	27%	2.14.E+05	27%	1.20.E+05	15%
6	0	2	7.04.E+05	100%	4.62.E+05	66%	3.04.E+05	43%	1.99.E+05	28%
	0	2	7.04.E+05	100%	2.73.E+05	39%	2.37.E+05	34%	1.89.E+05	27%
6	0	7	7.52.E+05	100%	4.65.E+05	62%	2.88.E+05	38%	1.78.E+05	24%
	0	7	7.52.E+05	100%	3.26.E+05	43%	2.39.E+05	32%	1.71.E+05	23%
6	0	3	5.88.E+05	100%	3.17.E+05	54%	1.70.E+05	29%	9.17.E+04	16%
	0	3	5.88.E+05	100%	1.65.E+05	28%	1.52.E+05	26%	8.71.E+04	15%
6	0	2	8.04.E+05	100%	5.42.E+05	67%	3.65.E+05	45%	2.46.E+05	31%
	0	2	8.04.E+05	100%	4.71.E+05	59%	3.03.E+05	38%	2.43.E+05	30%
6	0	7	7.60.E+05	100%	5.63.E+05	53%	4.17.E+05	53%	3.09.E+05	37%
	0	7	7.60.E+05	100%	4.39.E+05	58%	3.67.E+05	48%	3.00.E+05	39%
6	0	3	7.28.E+05	100%	4.99.E+05	69%	3.42.E+05	47%	2.35.E+05	32%
	0	3	7.28.E+05	100%	4.74.E+05	66%	2.67.E+05	41%	2.30.E+05	32%

It can be seen that the duration of ultrasonic exposure impacted algae removal, both in vacuum and non-vacuum conditions.

The experiment under non-vacuum conditions clearly indicated that relatively low power intensity and frequency could only achieve up to 57% removal within 180 minutes, which may suggest that the energy input from ultrasound was not sufficient to disrupt or de-clump algal cells [7]. On the other hand, vacuum conditions gave better removal of algal cells (up to 92% removal within 180 minutes). When the negative pressure condition occurs, the production of cavitation bubbles will be increased to disrupt the algal cells [13]. This experiment showed that the vacuum condition has a greater influence than the non-vacuum condition.

Effect of Ultrasonic Duration on the Removal of Algae Under Vacuum and Non-vacuum Conditions

In Figure 2, it can be seen that with an average transducer power of 3.84 watts and the transducer's average depth to the water surface at 0.13 m, the longer the ultrasonic exposure in water, the smaller the remaining number of algae resulting from the ultrasonic removal. In addition, vacuum conditions provided better algae removal results.

According to Eq. (2), in a situation where x (depth between transducer and air surface), Pw (ultrasonication power), constant frequency, and exposure are in the same time range, it can be seen that Ct/Co (algae residue after ultrasonication) in a vacuum will be lower than in a non-vacuum condition. This follows the phenomenon that the cavitation or boiling of water is faster when the air pressure above the water is lower or in a vacuum. This phenomenon is explained by the H_2O phase change in the P-T diagram. Ultrasonication will cause positive-negative vibrations that alternate with high frequency when the negative cavitation vibration is greater when the air pressure at the water's surface is lower or in a vacuum. The lower the air pressure on the surface of the water, the higher the cavitation effect, which will further damage the structure of the algae (lysis) contained in the water.

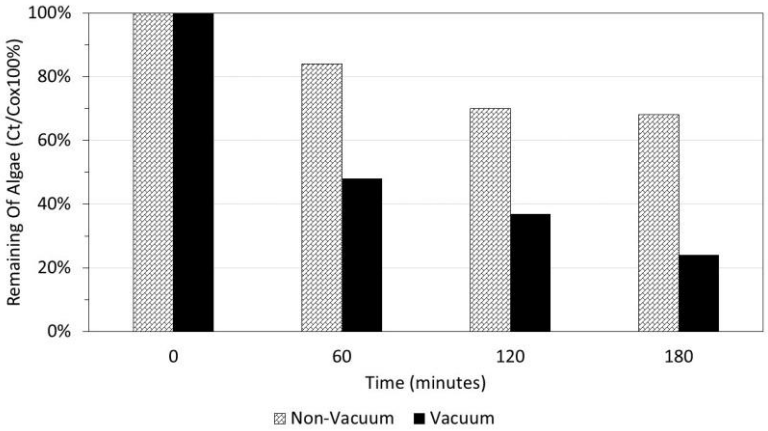

Figure 2 Effect of ultrasonic duration on the percentage of the remaining algae.

The concentration of the remaining algae in the experiment was as shown in the graph in Figure 3, following the first-order decay equation $Ct/Co = e^{-K \cdot t}$. This equation follows the experiment of Fan *et al.* (2014), where the equation here was used as the basis for modeling the calculation of the remaining algae during ultrasonication. Also according to Fan, the pseudo constant K is considered to be exponential with the effect of vibration or Ct/Co = $e^{-K \cdot f \cdot t}$. Following the model proposed here, as in Eq. (2), the constant K is affected by changes in air pressure on the water surface, the depth of the transducer to the water surface, and the ultrasonication power so that the equation of the remaining concentration of algae is Ct/Co = $e^{-F(\Delta P, x, Pw) \cdot f \cdot t}$.

Effect of Transducer Depth on Vacuum and Non-Vacuum Condition

Figure 3 shows that the transducer power was 3.84 watts and the average pressure change was 67 N/m^2. The greater the depth between the transducer and the water surface, the greater the number of algae remaining

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after ultrasonic removal. The distance to the water surface affects the hydrostatic pressure, which will adversely disturb the cavitation process. The greater the hydrostatic pressure, the smaller the cavitation effect. This is caused by the depression effect on the transducer's performance, which enervates the ceramic media vibration at the transducer. Mathematically, the cavitation effect can be expressed as the reverse of depth; thus, if x is the depth, the transducer effect will be the function of 1/x. Figure 3 shows that the longer the process, the greater the deviation, while the deviation also increases in a vacuum state. This implies that the longer the ultrasonic irradiation under vacuum, the more unpredictable the algae remaining will be. This is in agreement with the previous study by J. Park *et al.* (2019), i.e., the effect of ultrasound on the removal of algae rapidly decreases over the distance from the ultrasound transducer. Therefore, a reactor configuration with shorter distances from the ultrasonic transducer is needed to give better performance.

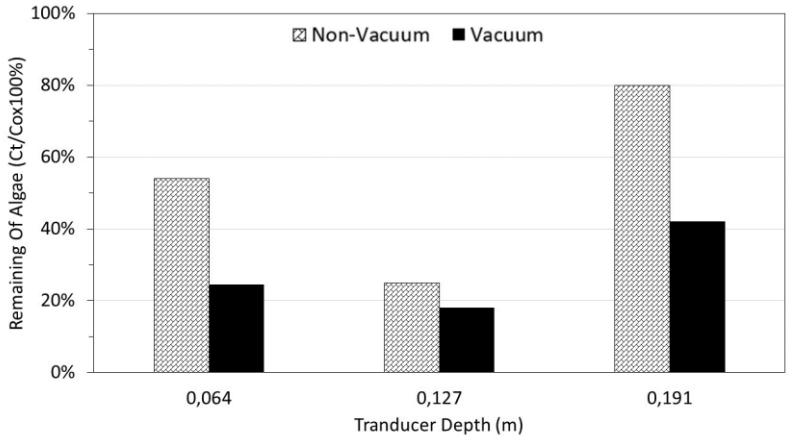

Figure 3 Effect of transducer depth on the percentage of remaining algae.

Effect of Ultrasonic Power-to-volume on Remaining Algae Concentration under Vacuum and Non-vacuum Condition

In Figure 4, the transducer power is 3.84 watts, and the average transducer distance to the water surface is 0.13 m. The greater the transducer power, the smaller the remaining algae after ultrasonic removal. The distance here represents the role of hydrostatic pressure on the surface of the transducer, so the smaller the hydrostatic pressure on the transducer, the greater the effect of ultrasonic algae lysis. This result is similar to the previous study reported in [14], with power generally being an important parameter in sonochemistry, an increase in power produces an increase in the energy input into the system during specific exposure times (i.e., dosage) for cell disruption.

The experiment extended the parameters by applying negative pressure during the ultrasonication of the water specimens. It showed that lower pressure produces more algae removal at the same power intensity. This implies that the same amount of energy used in ultrasonication by reducing the atmospheric pressure above the water surface will produce a more significant destruction effect on the algae cells. This phenomenon is confirmed by [15], where the kinetic formula for the ultrasonication model was affected by power (watts), the distance of the transducer to the water surface (m), external pressure (Pa or N/m^2), and frequency (1/s).

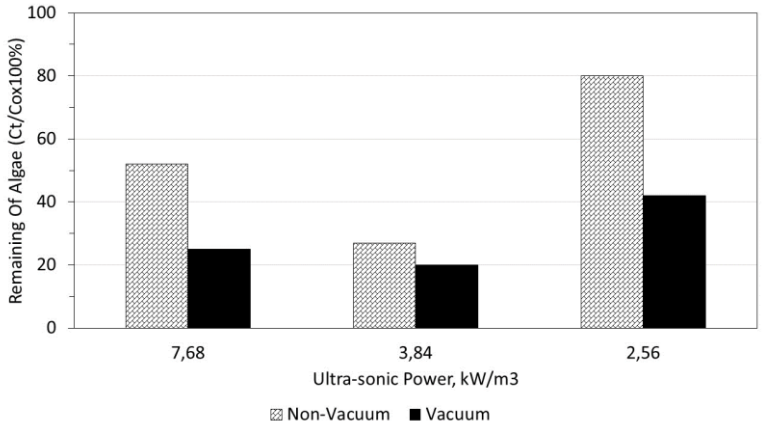

Figure 4 Effect of ultrasonic power on the percentage of remaining algae.

Effect of Air Pressure P, Exposure Power (Pw), and Transducer Position (x) on Algae Remaining Percentage

Based on Eqs. (4) and (5), the coefficients (K1 and K2) could be calculated by using multiple regression methods with the values of K1, and K2 at 9.31.10-11 m^2/N and 9.97.10-11 m^2/N), respectively. By substituting these coefficients, Eq. (2) could be derived to give Eq. (4). Coefficients ρ and g can merge to K2. Therefore, Eq. (4) can be transformed into Eq. (5).

$$\frac{Ct}{Co} = \mathbf{e}^{\left(K_1.\Delta P + K_2.\frac{\sqrt{Pow}}{x}\right).\mathbf{f}.\mathbf{t}} \tag{5}$$

Eq. (5) could correctly estimate the effect of ultrasonication on algae reduction at the various atmospheric levels and transducer positions below the water surface.

Figure 5 shows that the power-to-depth ratio in the process affects the number of remaining algae. Lower atmospheric pressure on the water surface will reduce the remaining algae concentration. The concentration deviation of the process was smaller at the lower power-to-depth ratio compared to the higher ratio. This implies that the higher the power-to-depth induced [9,14], the more volatile the process result. Furthermore, it also shows that in a vacuum state, the deviation of the remaining algae is more significant than in a non-vacuum state [13]. Therefore, it can be concluded that the process will be more volatile at a high power ratio in a vacuum.

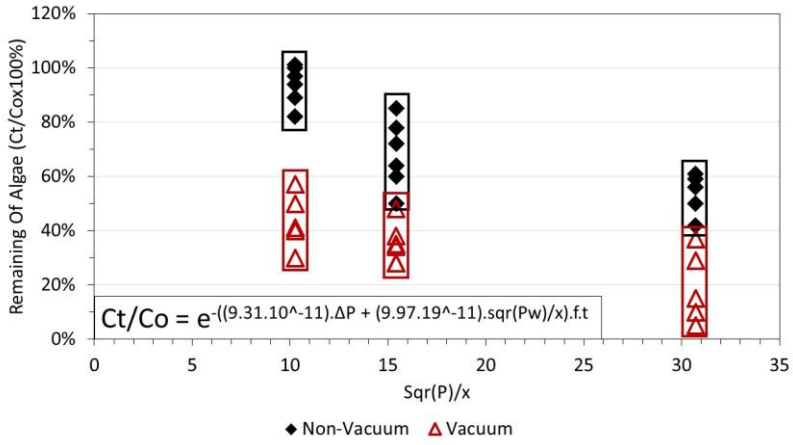

Figure 5 Effect of air pressure P, exposure power (Pw), and transducer position (x) on the percentage of the remaining algae at f = 20 kHz and t = 180 minutes and its deviation.

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Relation between the Transducer Depth and the Effectiveness of the Transducer Power

Regarding Eq. (5), by integrating variable ln(Ct/Co), f, t, and ΔP, which is assumed to be in a constant state, in Kx, Eq. (6) can be developed.

$$Kx = \frac{(K_1.)^2}{\left[\frac{ln\left(\frac{C_t}{C_O}\right)}{f.t} - K_2.\Delta P\right]} \quad (6)$$

Then by substituting Eq. (6) into Eq. (5), the power equation becomes:

$$Pow = K_x.x^2 \quad (7)$$

This implies that every portion of the depth reduction will reduce the power in the square. In contrast, for every portion of depth escalation, more power in the square should be applied to achieve the same algae removal result. Therefore, the minimum depth of the transducer should be used to obtain minimum power consumption.

Microscopy Algae Remaining

Most surface water in Indonesia has been polluted with high concentrations of pollutants (e.g., algal bloom) and it is important to develop non-conventional treatment technologies such as ultrasonication [16,17]. In this study, observations were made using a microscope to determine the process of algae removal. Figure 6 shows the concentration of algae at the initial state, and Figure 7 shows the change in the algae concentration after ultrasonification.

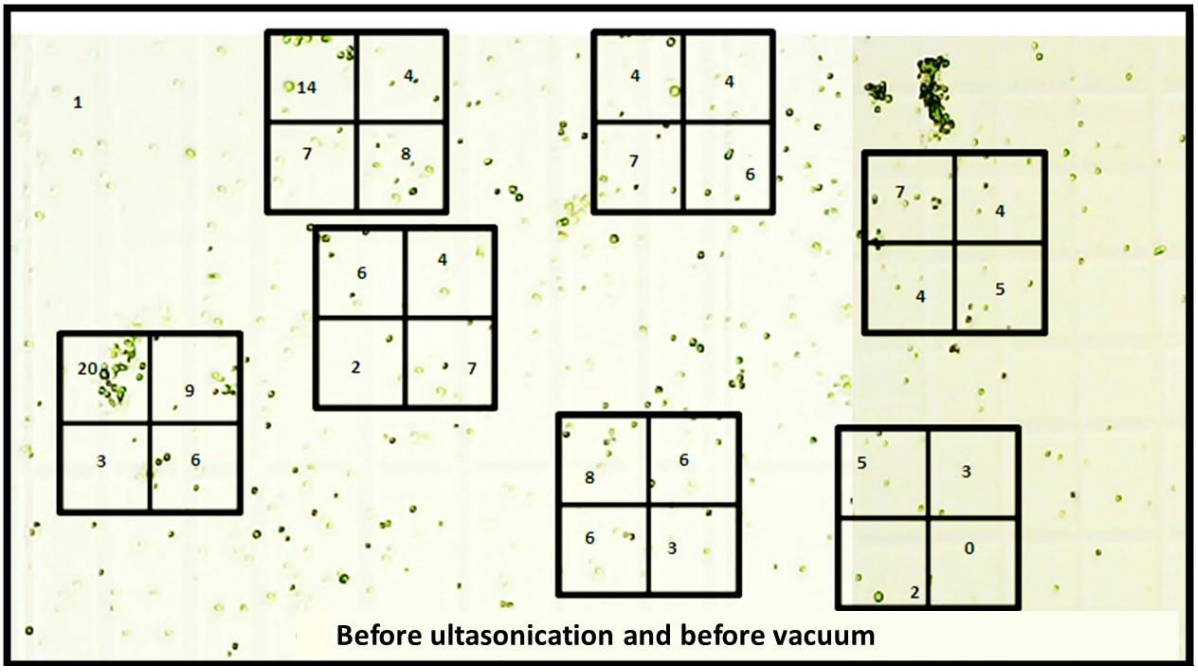

Figure 6 Concentration of algae at time 0, before ultrasonication and before vacuum.

Figure 7 shows that the algae remaining in the vacuum was reduced significantly compared to the non-vacuum. Furthermore, the remaining algae could be eliminated by other processes, such as microfiltration, slow sand filter, through coagulation, flocculation, and sedimentation.

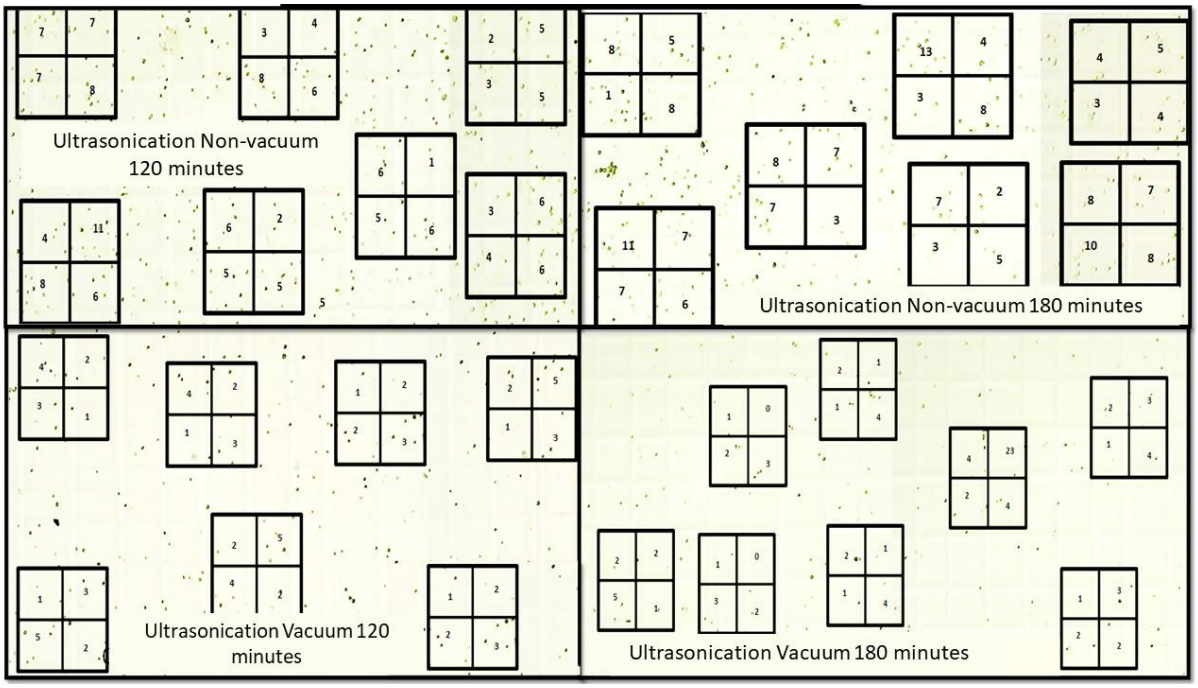

Figure 7 Differences in changes in the concentration of algae at times 120 and 180 minutes in non-vacuum (a) and vacuum (b) conditions.

Conclusion

In this study, the effects of ultrasound on the suspension of Chlorophyta-chlorella sp. were investigated with a power of around 3.18 watts, a frequency of 20 kHz, under a vacuum of (ΔP = -67 N/m^2) and a non-vacuum state (ΔP = 0 N/m^2), and at various ultrasonic charging depths (0.064 m, 0.127 m, and 0.191 m). Under ultrasonication, algal cells ruptured and improved cellular sedimentation, helping to remove algae cells from the water. The optimum conditions (92% algae cell disruption) occurred when the power intensity was 7 kWh/m^3, under vacuum conditions, and within 180 minutes of exposure time. Moreover, this study also revealed that the same amount of energy used in ultrasonication in a vacuum state reduced the number of remaining algae.

Besides reducing atmospheric pressure above the water, ultrasonic transducer depth at the water surface has a significant effect. This is caused by the hydrostatic pressure on the ceramic at the transducer. An inverse effect on the remaining algae will occur. The more critical the hydrostatic pressure, the smaller the cavitation effect caused by the depression effect on the transducer performance, which enervates the ceramic media vibration at the transducer. Eq. (7) shows that the power consumption is related to the square of the transducer depth. The cavitation effect is the reverse of depth. This means that an increase in the power-to-depth ratio will increase the algae reduction. Therefore, the adjustment of atmospheric conditions and the power-to-depth ratio is critical in the process.

Despite the benefit of reducing the pressure in the ultrasonication process, two issues should still be resolved. These are: (1) how to provide adequate constant negative pressure, and (2) how to maintain constant continuous flow through the process. Hopefully, in the future, this technology will find application for removing algae from water.

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