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Mass Transfer Study for Bio-Synergy in Dairy Wastewater Treatment Plant

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ABSTRACT

The present study addresses the behavior of gases in cultivation media as an essential factor to develop the relationship between the microorganisms that are present in the same environment. This relationship was explained via mass transfer of those gases to be a reasonable driving force in changing biological trends. Stripping and dissolution of oxygen and carbon dioxide in water and dairy wastewater were investigated in this study. Bubble column bioreactor under thermal control system was constructed and used for these processes. The experimental results showed that the removal of gases from the culture media requires more time than the dissolution. For example, the volumetric mass transfer coefficient for the removal of oxygen is 1.67 min^{-1} while the volumetric mass transfer coefficient for dissolution the same gas is 3.18 min^{-1}. The same thing occurred with carbon dioxide, where the data showed that the volumetric mass transfer coefficient of the dissolution of CO_2 is 0.66 min^{-1} while the volumetric mass transfer coefficient for removal process is 0.374 min^{-1}. However, the two processes (dissolution and removal) with CO_2 take more time than that with O_2. Therefore, the production of gases due to metabolic processes in bacteria or microalgae remains in culture's media for a certain period even if that media is sparged by air. Thus, this will give enough time for both microorganisms to consume those gases.

Keywords: Bioreactor, mass transfer, microalgae, aerobic bacteria

دراسة انتقال الكتلة للتآزر الحيوي في وحدة معالجة مخلفات اللألبان المائية

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الخلاصة

تناولت الدراسة الحالية سلوك الغازات في الوسط الزراعي كعامل أساسي لتطوير العلاقة بين الكائنات الحية الدقيقة الموجودة في نفس البيئة. وقد تم شرح هذه العلاقة عن طريق النقل الجماعي لتلك الغازات لتكون قوة دافعة معقولة في تغيير الاتجاهات البيولوجية. تجريد واذابة الاوكسجين وثاني اوكسيد الكاربون في الماء ومخلفات الالبان المائية تم التحقق

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منها في هذه الدراسة. تم بناء المفاعل الحيوي نوع العمود الفقاعة تحت نظام التحكم الحرارة واستخدامه لهذه العمليات. بينت نتائج التجارب أن إزالة الغازات من الوسط الزرعي يتطلب وقتا أطول من اذابتها. على سبيل المثال معامل نقل الكتلة الحجمي لإزالة الأوكسجين هو 1.67 لكل دقيقة، في حين أن معامل نقل الكتلة الحجمي لذوبان الغاز نفسه هو 3.18 لكل دقيقة. نفس الشيء حدث مع ثاني أكسيد الكربون، حيث أظهرت البيانات أن معامل نقل الكتلة الحجمي لذوبان CO_2 هو 0.66 لكل دقيقة في حين أن معامل نقل الكتلة الحجمي لعملية الإزالة هو 0.374 لكل دقيقة. ومع ذلك، فإن العمليتين (الاذابة والإزالة) مع CO_2 يستغرق وقتا أطول من ذلك مع O_2. ولذلك، فإن إنتاج الغازات الناجمة عن عمليات التمثيل الغذائي في البكتيريا أو الطحالب الدقيقة لا يزال باقية في الوسط الزرعي لفترة معينة حتى لو كان ذلك الوسط زود بفقاعات هوائية. وبالتالي، فإن هذا سيعطي الوقت الكافي لكلا الكائنين الحية الدقيقة لاستهلاك تلك الغازات.

الكلمات الرئيسية: مفاعل حيوي، انتقال كتلة، طحالب، بكتريا هوائية

1. INTRODUCTION

The accelerated global demand for energy is still a concerning factor for many researchers and for those interested in the environment and energy fields **Schenk, et al., 2008**. It is related to fossil fuels consumption and its economic and environmental effects, **Dryzek, 2011**. Despite the availability of alternatives to conventional fuels, the productivity still suffers from high costs and low production. **Chisti, 2007**. Furthermore, some of those alternatives are in a competitive position with world food demand **Scott, et al., 2010, Singh 2012 and Hettinga, et al., 2009**. For instance, biofuels produced from some agricultural crops require large areas of arable land with water for cultivation purpose **Liu, et al., 2016**. In fact, these crops can meet the needs of poor countries to prevent famine **Rosgaard, et al., 2012**. In contrast, the development in the field of industry produced large quantities of wastewater. In addition to its contribution to the already worsening energy problems, the resulting wastewater, and its environmental pollutants have become an obstacle to these developments. These pollutants are related to human health, especially those produced from the food industries. For this reason, it became necessary to use applied studies to address industrial problems and minimize energy requirements. This can be accomplished by identifying the most efficient means of exploiting bioenergy sources to provide the necessary energy. Nevertheless, that process, if accompanied by the improvement of the source itself, it will increase the benefits to the maximum extent possible. Indeed, the present study seeks to investigate this hypothesis.

There are many attempts that have been made to utilize organic materials that available in food wastewater by the cultivation of the microalgae as a source of bio-carbon dioxide for bacteria **Sutherland, et al., 2014, Satpal and Khambete, 2016, and Aravantinou, et al., 2013**. The microalgae are also an important source of renewable energy, which has revolutionized its development in recent years **Banerjee, et al. 2002, Abou-Shanab, et al., 2011, Chisti, 2007**. It represents a promising source for different productions **Choi, 2011**. Based on some studies, half of their dry weight is oil content that can be extracted to be an environmentally friendly fuel and a good alternative to fossil fuels **Chisti, 2007**. One kilogram of the dry weight of biomass requires about double of carbon dioxide. However, these attempts still face some challenges, including the cost of agriculture and selectivity suitable for agriculture. In fact, the most appropriate selection is the most prevalent in the area of agriculture, as these species are able to survive in the same conditions. There are several studies that have included the cultivation of microalgae in dairy waste **Choi, 2016, Woertz, et al., 2009, Hena, et al., 2015**, but the operating conditions, microalgae species, and type of study case may differ from research to another.

Cultivation of microalgae in such a type of solutions and in accordance with these operational conditions makes it a forced confrontation with other microorganisms, such as aerobic bacteria and anaerobic bacteria. The preference for aerobic bacteria over anaerobic bacteria depends on the quality and quantity of available oxygen sources. Indeed, the microalgae, if they are found in isolation from other microorganisms, can improve their productivity by eliminating the accidental product (oxygen) of their metabolic processes **Molina, et al., 2001, Raso, et al., 2012**. The increase in oxygen causes an imbalance in metabolic bio-reactions according to Le Chatelier's concept, which shows the response of balanced reactions to change their direction due to increased or decreased concentration of the products. Thus, thermodynamically, the free energy of these reactions will turn to positive values. Consequently, there will be no benefit from the solar energy adenosine triphosphate (ATP) to convert the non-spontaneous reactions to the fact that the concentration of products has become too difficult to proceed with the metabolic processes. Therefore, it is possible to have a significant inhibiting in the reproduction of microalgae in these conditions. This can also happen to aerobic bacteria despite the fact that their biological reactions are spontaneous. The free energy of these interactions may also turn into positive values if their products increase.

However, the presence of these two species of organisms may radically change the scenarios through the principle of co-existence and mutually beneficial. Because of the subject has become under the circumstances of changing phases, it is worth and through the current research is an urgent need in the study of the mass transfer of products gases in water and water residues selected for the current study according to a hypothesis.

The hypothesis of the current research suggests that the possible co-existence between the microalgae and bacteria in the same place and environment can be determined by the gas-transfer factor from those organisms. Therefore, the present paper seeks to investigate this hypothesis through the volumetric mass transfer coefficient.

2. MATERIAL AND METHODS

2.1 Experimental set-up

Cylindrical bioreactor with a diameter of 120 mm and 260 mm height was used for mass transfer study as shown in **Fig.1**. The reactor was provided by a ceramic diffuser (diameter 80mm) for sparging system purpose. Dairy wastewater and distilled water were used as solutions in this study, while air, nitrogen, oxygen, and carbon dioxide were used as gases. These gases were provided by the flow rate for each gas was 500 ml/min in dissolution and removal process. The hydrogen ion (pH value) was measured regularly using (pH-Basic 20, CRISON), while the dissolved oxygen was measured using (OXI 45+, CRISON, Spain). All the data were recorded during the experiments. The temperature of the solution was controlled with 30^{o}C using heating control system. **Fig. 2** shows the screenshot of the experimental set-up used in the present study. Table 1 shows the operation conditions and bioreactor dimensions.

2.2 Collection of dairy wastewater

The wastewater produced from the dairy factories was collected from the General Company for Food Industry in Abu Ghraib City. In fact, the environmental and location conditions of the dairy wastewater treatment unit plant play an important role in selecting the suitable location for microalgae cultivation. Dairy waste is rich in fatty substances as well as suspended solids. Removal of these substances is necessary for the cultivation of microalgae because they block the required light for the photosynthesis of the cells. In addition, deposition may contribute somewhat to the adhesion of organic materials and stack down the reactor, and thus will cause nutrients-layers in the same reactor. The selection of nutrition for cultivation in this microorganism was after the processes of fat reduction and preliminary processing.

2.3 Calculation of Mass transfer coefficient

Generally, the gas is a major requirement in the growth of some organisms. It may limit the growth rate of these microorganisms. Optimal growth rate can be achieved when the solubility of that gas is maintained at a higher level slightly than the critical level. High concentration of gases will not work in improving growth rate as well as not be an important determinant of the growth rate of the microorganisms. Therefore, the strategy of the current research has been based on this principle by providing the necessary gas for the growth of bacteria and microalgae, with opportunities for mutual benefit between them. Thus the rate of transfer of carbon dioxide and oxygen gas should exceed the requirement of microalgae and bacteria, respectively. The current study relied on the identification of this strategy through a study the mass transfer gases via volumetric mass transfer coefficient (K_La). This coefficient, which includes the surface area between the transition zones, depends mainly on the concentration of the substance in the two phases as they change with time. The molar flux in gas-liquid systems can be writing as the following:

$$J_A = k_G \times (P_G - P_i) = k_L \times (C_i - C_L) \qquad (1)$$

Where J_A is the molar flux of gas (mol/m^{2}s), k_G and k_L are the local gas mass transfer and local liquid mass transfer coefficients respectively, P_G and P_i are partial pressure of the gas in the gas phase and interface area respectively, and finally, C_L and C_i are gas concentration in the liquid phase and interface area respectively.

It is difficult to measure the concentration or partial pressure in the interface zone. Therefore, it replaced by saturated or equilibrium concentration or equilibrium pressure. In the present study, both parameters were used for oxygen and carbon dioxide, as given in equation (2).

$$J_A = k_G \times (P_G - P^*) = k_L \times (C^* - C_L) \qquad (2)$$

From the equation, it can be obtained by the following equation:

$$\frac{dC}{dt} = K_L a\,(C^* - C_L) \qquad (3)$$

By integration of the above equation, the following equations can be used for removal and dissolution of the gases:

$$\ln\left(1 - \frac{C_{Lt}}{C^{eq}}\right) = -K_L a\, t \qquad (4)$$

$$\ln\left(1-\frac{C_{Lo}}{C_{Lt}}\right)=K_L a\ t \qquad (5)$$

Where C_{Lo} is initial concentration, C_{Lt} is the concentration at the time, C^{eq} is the concentration at equilibrium state, and t is a time of dissolution or stripping process.

By drawing the parameter in the right-hand side against time, the slop will be volumetric mass transfer coefficient ($K_L a$).

3. RESULTS AND DISCUSSION

In general, the presence of gas bubbles in biological systems is necessary to achieve food homogeneity and prevent the formation of thermal layers in the parts of the reactor. Oxygen, nitrogen, hydrogen sulfide, hydrogen, and methane are the most abundant gases in those systems. These gases either enter as basic substances in the metabolic processes, or they are products of them. However, some of these gases can be used in biological processes to achieve the desired target. In the present study, aeration using air was suggested in the sparging system with microalgae.

The concentration of oxygen in water is limited by its concentration in the environment. With the known oxygen concentration in the air, it is inconceivable that the concentration of oxygen in the water will exceed 7-9 mg/liter. Therefore, the experiments conducted in the current research have proved this fact. Using air in the sparging system enhances the concentration of oxygen within certain limits as can be seen in the **Fig.3**. However, using a higher concentration of oxygen in the gas phase can increase the equilibrium concentration in the sparged liquid.

Fig. 4 shows the dissolution and removal of oxygen in the distilled water. The removal process was carried out using pure nitrogen. The oxygen remains as a free gas in water, however, the solubility of oxygen is faster than its removal as can be seen in the figure. Consequently and according to the calculations conducted in this research, the volumetric mass transfer coefficient in the solubility process is greater than that in the removal process. For instance, the K_La of the dissolution of oxygen in water was about 3.18 min^{-1}, while in the removal process using the nitrogen the K_La was about 1.67 min^{-1} as can be seen from **Fig. 5**.

To determine the rate of consumption of aerobic bacteria for oxygen, experiments were conducted around that consumption through the process of sparging to a bioreactor containing 2.4 liters of non-sterilized wastewater without any microalgae culture available in the media. The sparging system was carried out at 30^{o}C. Once the state equilibrium is achieved, the pumping system stops and the dissolved oxygen are then monitored in the wastewater. The same procedure is repeated with the distilled water, but the removal is done by sparging with pure nitrogen. **Fig. 6** shows the amount of oxygen consumption by bacteria when there are no microalgae available in the same media, while the second line represents the removal of oxygen in mg/l from distilled water when the bioreactor was sparged by 500 l/min of pure nitrogen for comparison. It can be seen, in the natural removal by bacteria, about 20 minutes enough to drop the dissolved oxygen from 6 mg/l to 0.05 mg/l.

Leaving the bioreactor without aeration system, the environment will gradually turn into an oxygen-free, except for the layers that are in contact with the atmosphere. Thus the growth of anaerobic bacteria will be possible. However, the presence of microalgae reduces the likelihood of this change by processing the solution with bio-oxygen in all areas of the reactor. This is one of the advantages that have been concluded from this current research since it will reduce the consumption of electrical energy in the biological treatment units of the dairy wastewater.

The delay in depletion of the oxygen represents a significant factor in achieving the current research idea since its existence in media provides sufficient time for the bacteria to consume it. Moreover, the rapid growth of bacteria is also a driving force for consumption the oxygen as quickly as possible, as observed in **Fig. 6**.

The solubility of carbon dioxide in distilled water is also faster than removing it. In addition to its similar behavior to the oxygen gas, solubility and stripping process, it takes longer to remove as can be seen in the **Fig.7**. This figure displays the volumetric mass transfer coefficient of the dissolution and removal of CO_2 from the water. K_La of dissolution is 0.66 while K_La for removal process is 0.374 m^{-1}. However, the two processes (dissolution and removal) with CO_2 take more time than with O_2. In fact, the presence of carbon dioxide in the water is a physiologic presence. However, a certain amount of this gas reacts with water to produce carbonic acid and its ions as shown in the reactions below.

$$CO_{2(g)} \longleftrightarrow CO_{2(aq)} \qquad (6)$$

$$CO_{2(aq)} + H_2O \longleftrightarrow H_2CO_3 \qquad (7)$$

$$H_2CO_3 \longleftrightarrow HCO_3^{-1} + H^{+1} \qquad (8)$$

$$HCO_3^{-1} \longleftrightarrow CO_3^{-2} + H^{+1} \qquad (9)$$

Although the reaction ratio of carbon dioxide to water is quite low, the concentration of hydrogen produced from these reactions has a significant effect on the pH value. This value reduces to three for just four minutes, while removing the carbon dioxide requires longer time. The fact these microorganisms have a sufficient time to take advantage of that biogas.

However, **Fig. 8** shows that solubility of gases in the distilled water is different from that of wastewater. This difference proves that the soluble and suspended substances significantly affect the solubility and removal of gases. Nevertheless, this research addresses a culture media containing effective microorganisms that consume and produce gases during the process of studying volumetric mass transfer coefficient. Therefore, the gas removal problem does not need to use nitrogen gas in this study for the removing oxygen purpose, since the bacteria in this solution is a good consumption. Thus, oxygenation was carried out with external action with monitoring and control systems. While consumption of oxygen was carried out by bacteria with monitoring systems as shown in **Fig. 8**.

However, the comparison between oxygen dissolution and removal by bacteria, as in **Fig. 9.** It shows that oxygenation is faster than stripping process, since the K_La for dissolution of oxygen in dairy wastewater was about 0.3 min^{-1}, while in removal process via the bacteria the K_La was about 0.09 min^{-1}. This means that aerobic bacteria have time to consume this amount of dissolved oxygen. Effective bacteria and operational conditions used in this study require only 18 minutes to consume all dissolved oxygen in the culture media. Therefore, this rate of consumption, if not combined with another source of oxygen, will gradually turn the culture media into an anaerobic environment.

4. CONCLUSIONS

The mass transfer rate of oxygen and carbon dioxide as sub-products gases in non-sterilised dairy wastewater was investigated in the present study. The volumetric mass transfer coefficient of the dissolution of oxygen in water was about 3.18 min^{-1}, while in the removal process using the nitrogen the K_La was about 1.67 min^{-1}. The same thing was observed with the dissolution of oxygen and carbon dioxide in water. However, and because of the chemical reactions of the carbon dioxide with its ions, the two processes take longer time than that with oxygen. In addition, the characteristics of the dairy wastewater play an important role in the two processes. Nevertheless, this behavior may give sufficient time advantage to bacteria and the microalgae for the consumption of biogas resulting from the metabolic processes via mutually beneficial principle.

5. NOMENCLATURES

Parameter	Meaning	Unit
J_A	The molar flux of gas	$mole.m^{-2}. s^{-1}$
K_G	Mass transfer coefficient in the gas phase	
P_G	The partial pressure of the gas in the gas phase	atm
P_i	The partial pressure of the gas in the interface of area	atm
K_L	mass transfer coefficient in liquid phase	
C_i	Concentration in the interface of area	$Kg. L^{-1}$
C_L	Concentration in the liquid phase	$Kg. L^{-1}$
K_La	Overall mass transfer coefficient	m^{-1}
C_{Lo}	Initial concentration	$Kg. L^{-1}$
C^*	Saturated concentration	$Kg. L^{-1}$
t	time	min
P^*	Saturated pressure	atm
C^{eq}	Equilibrium concentration	$Kg. L^{-1}$

6. REFERENCES

- Abou-Shanab, R. A. I., Hwang, J. H., Cho, Y., Min, B. and Jeon, B. H. 2011. Characterization of microalgal species isolated from freshwater bodies as a potential source for biodiesel production. *Applied Energy,* Vol. 88, No. 10, PP. 3300-3306.
- Aravantinou, A. F., Theodorakopoulos, M. A. and Manariotis, I. D. 2013. Selection of microalgae for wastewater treatment and potential lipids production. *Bioresource Technology,* Vol. 147**,** PP. 130-134.
- Banerjee, A., Sharma, R., Chisti, Y. and Banerjee, U. C. 2002. Botryococcus Braunii: A renewable source of hydrocarbons and other chemicals. *Critical Reviews in Biotechnology,* Vol. 22**,** PP. 245-279.
- Chisti, Y. 2007. Biodiesel from microalgae. *Biotechnology Advances*, Vol 25, No. 3 PP. 294-306.
- Choi, H.-J. 2016. Dairy wastewater treatment using microalgae for potential biodiesel application. *Environmental Engineering Research*, Vol. 21, PP. 393-400.

- Choi, J. A., Hwang, J. H., Dempsey, B. A., Abou-Shanab, R. A. I., Min, B., Song, H., Lee, D. S., Kim, J. R., Cho, Y., Hong, S. and JEON, B. H. 2011. Enhancement of fermentative bioenergy (ethanol/hydrogen) production using ultrasonication of Scenedesmus obliquus YSW15 cultivated in swine wastewater effluent. Energy Environmental Science, Vol 4, PP. 3513-3520.
- Dryzek, J. S., Norgaard, R. B. and Schlosberg, D. 2011. *The Oxford handbook of Climate change and society: Approaches and Responses* Oxford University Press Inc., New York. Chapter one.
- Hena, S., Fatimah, S. and Tabassum, S. 2015. Cultivation of algae consortium in a dairy farm wastewater for biodiesel production. *Water Resources and Industry*, Vol.10, PP. 1-14.
- Molina, E., Fernández, J., Acién, F. G. and Chisti, Y. 2001. Tubular photobioreactor design for algal cultures. *Journal of Biotechnology*, Vol. 92, No. 2, PP. 113-131.
- Raso, S., Van Genugten, B., Vermuë, M. and Wijffels, R. H. 2012. Effect of oxygen concentration on the growth of Nannochloropsis sp. at low light intensity. *Journal of Applied Phycology*, Vol. 24, No. 4, PP. 863-871.
- Satpal, K. A. 2016. Waste Water Treatment Using Micro-Algae - A review Paper. *International Journal of Engineering Technology, Management and Applied Sciences,* Vol. 4**,** PP.188-192.
- Schenk, P. M., Thomas-Hall, S. R., Stephens, E., Marx, U. C., Mussgnug, J. H., Posten, C., Kruse, O. and Hankamer, B. 2008. Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production. *Bioenergy Research,* Vol. 1**,** No. 1, PP. 20-43.
- Scott, S. A., Davey, M. P., Dennis, J. S., Horst, I., Howe, C. J., Lea-Smith, D. J. and Smith, A. G. 2010. Biodiesel from algae: challenges and prospects. *Current Opinion in Biotechnology,* Vol. 21**,** No. 3, PP. 277-286.
- Singh, V. 2012. Effect of corn quality on bioethanol production. *Biocatalysis and Agricultural Biotechnology,* Vol. 1**,** No. 4, PP. 353-355.
- Sutherland, D. L., Turnbull, M. H. and Craggs, R. J. 2014. Increased pond depth improves algal productivity and nutrient removal in wastewater treatment high rate algal ponds. *Water Research,* Vol 53**,** PP. 271-281.
- Woertz; I., Feffer; A., Lundquist; T. and Nelson, Y. 2009. Algae Grown on Dairy and Municipal Wastewater for Simultaneous Nutrient Removal and Lipid Production for Biofuel Feedstock. *Journal of Environmental Engineering*, Vol. 135, No. 11.

Table 1. Operation conditions and dimensions of the vessel tank.

Parameter	**Value**	**Unit**
Flow rate	500	ml/min
Temperature	30	^{o}C
Volume of reactor	3	L
Liquid volume	2.6	L
Diameter of diffuser	80	mm

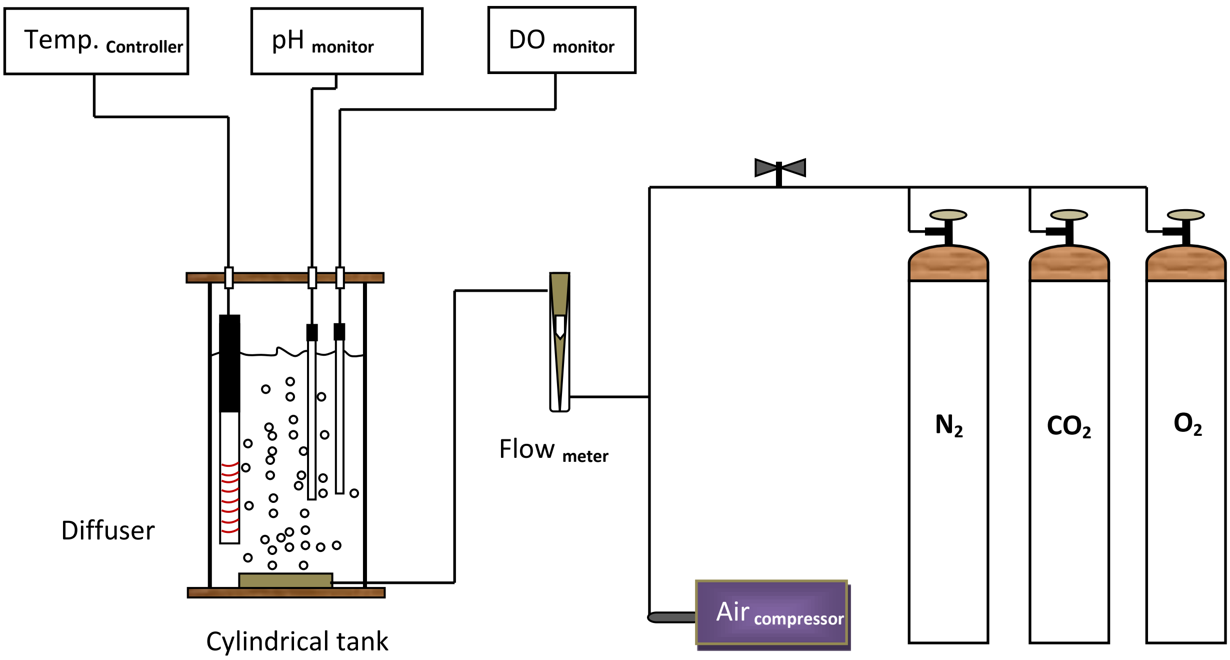

Figure 1. Schematic diagram of cylindrical tank used in mass transfer study.

Figure 2. Screenshot of the experimental set-up used in the present study.

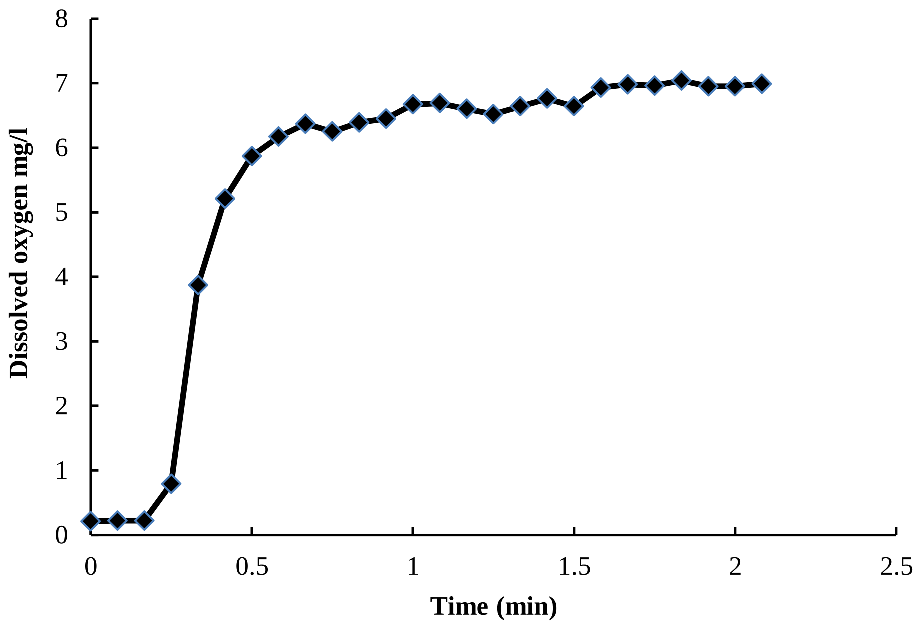

Figure 3. The oxygen concentration in distilled water at 30^{o}C when the air was used as gas is sparged.

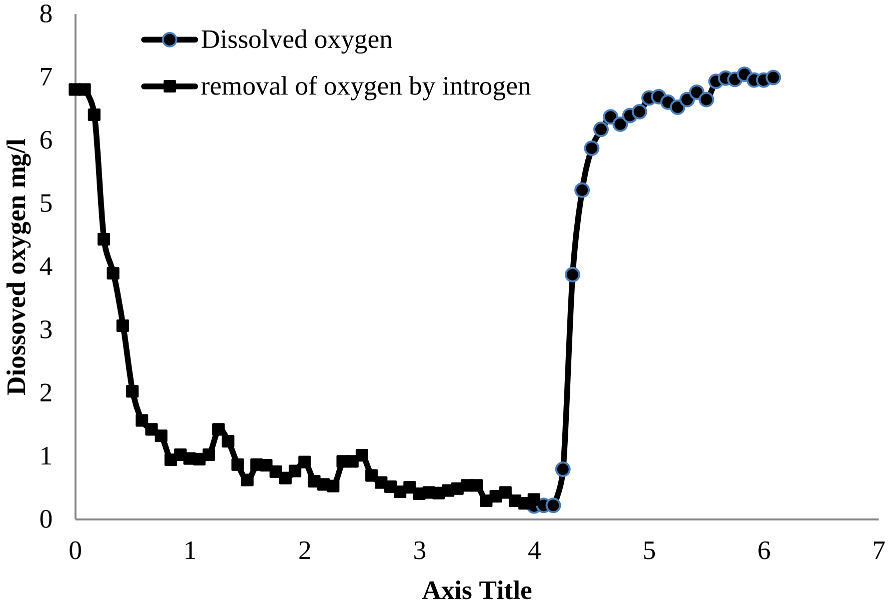

Figure 4. Dissolution and removal of oxygen in the distilled water.

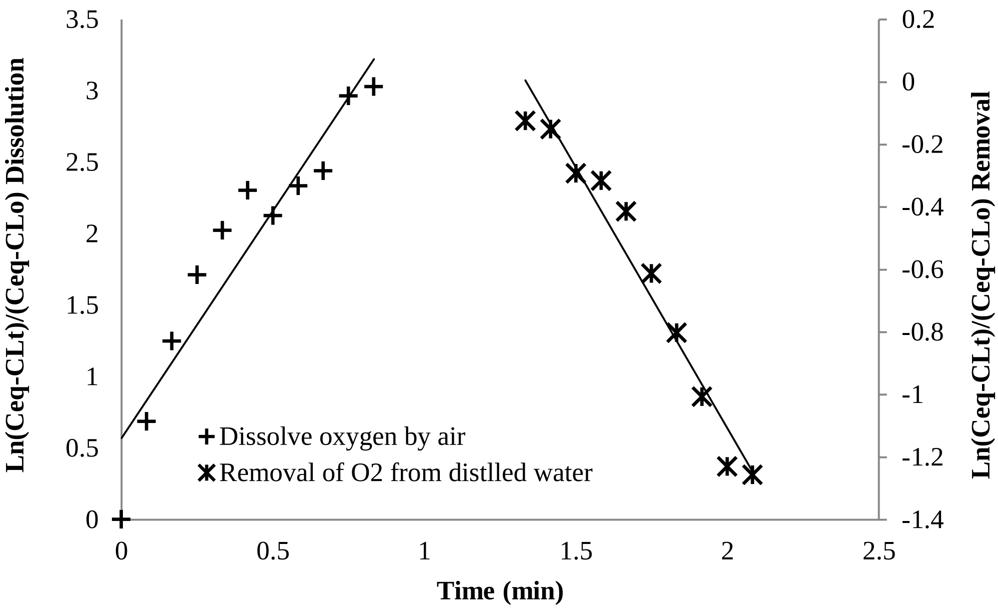

Figure 5. Volumetric mass transfer coefficient in dissolution and removal process with distilled water.

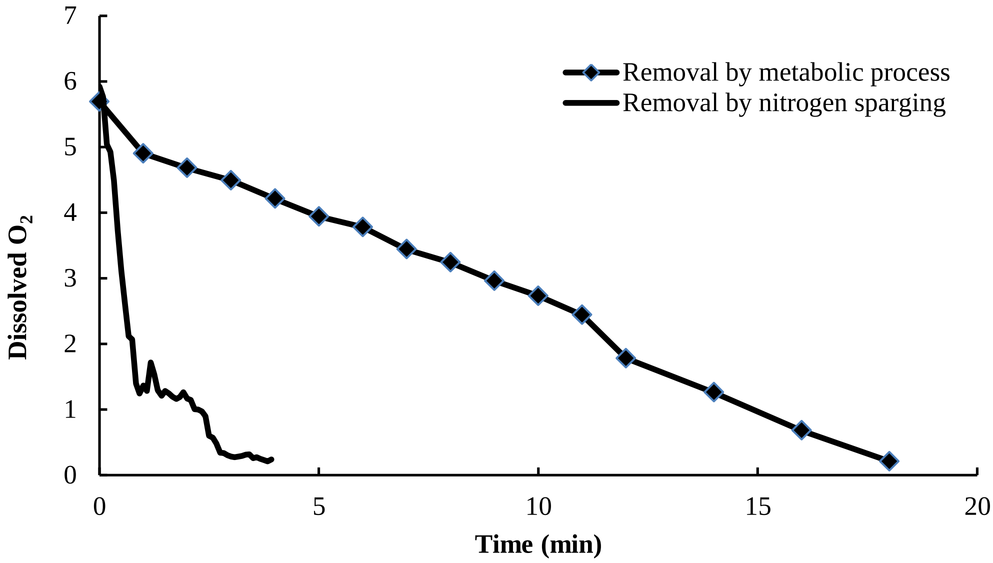

Figure 6. Dissolved oxygen in the distilled water, when the bioreactor removed by pure nitrogen, as well as in wastewater when the removal carried out by a metabolic process.

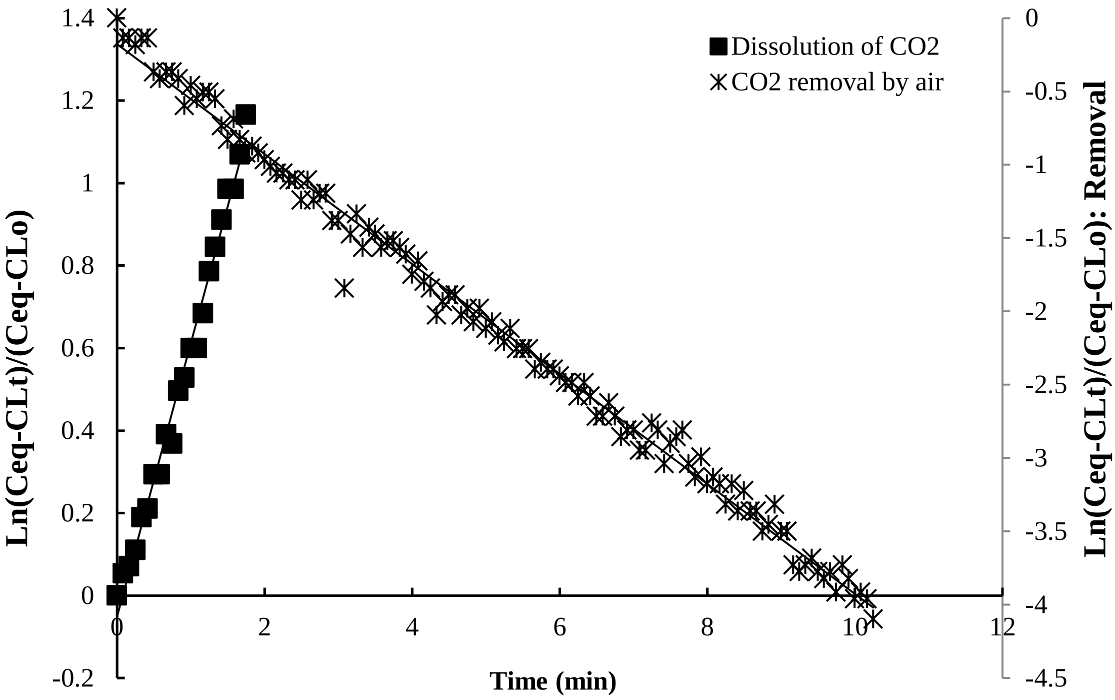

Figure 7. Volumetric mass transfer coefficient in dissolution and removal process with distilled water.

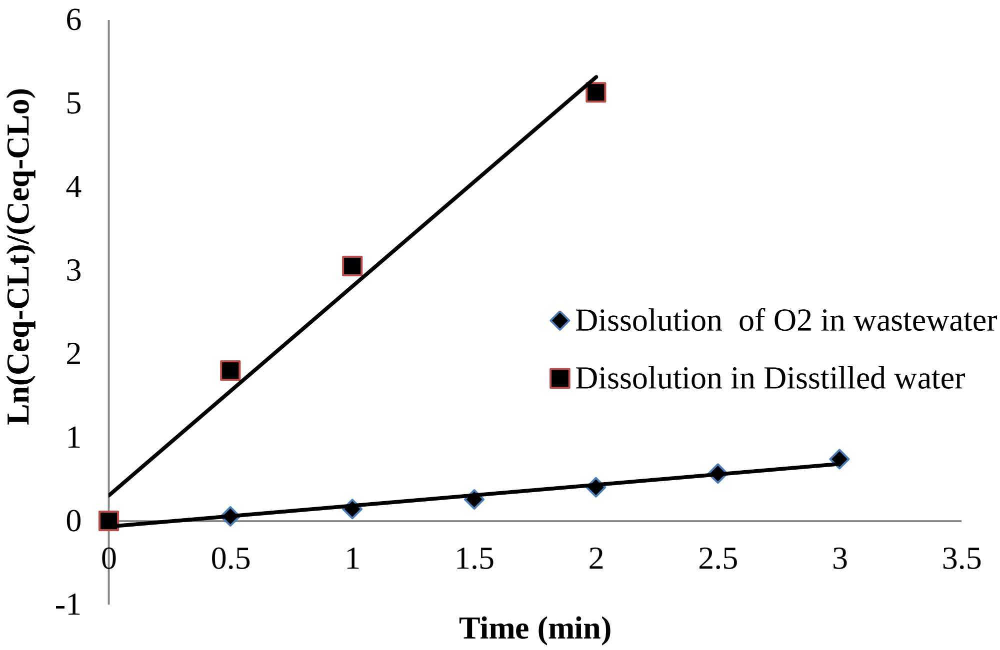

Figure 8. The volumetric mass transfer coefficient of dissolution of oxygen in wastewater and distilled water.

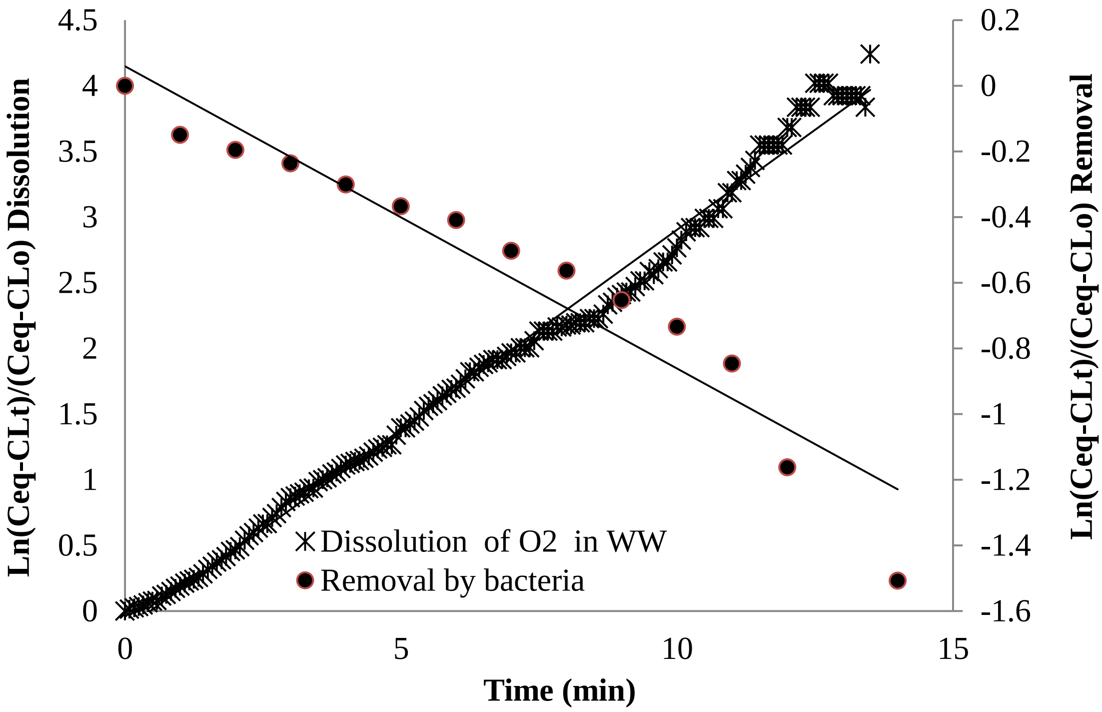

Figure 9. The volumetric mass transfer coefficient of dissolution in wastewater and removal process by metabolic processes.