

# Third-party imports

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib

# AIDE imports
import aide_design
import aide_design.pipedatabase as pipe
from aide_design.units import unit_registry as u
from aide_design import physchem as pc
import aide_design.expert_inputs as exp
import aide_design.materials_database as mat
import aide_design.utility as ut
import aide_design.k_value_of_reductions_utility as k
import aide_design.pipeline_utility as pipeline
import warnings
import scipy
from scipy import stats
import Environmental_Processes_Analysis as EPA
```

# CEE 4530 Final Project

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## Introduction and Context

Many organisms in various aquatic ecosystems are highly dependent on the dissolved oxygen (DO) in water in order to undergo aerobic respiration. These organisms are usually highly evolved to the specific niche that they occupy and fluctuations in DO levels in the water can significantly affect the well-being of these organisms.

Agricultural runoff from manure spreading often results in significant DO losses. When manure leaks into nearby ecosystems, the nutrients inside the manure are utilized by microorganisms in aerobic respiration, thus resulting in a depletion of DO. These nutrients are often rapidly utilized and the death of these microorganisms usually quickly follows. When these organisms die, their decomposition also significantly contributes to a drop in DO levels.

Sequencing batch reactors (SBR) are an effective method that can be used to remove nutrients from effluent wastewater. SBRs work by allowing an influent pollutant to react with microorganisms in order to undergo carbonaceous pollutant removal and then allowing the sludge to settle to the bottom of the reactor. Treated effluent and excess sludge is then pumped out of the reactor, thus yielding wastewater that has a reduced oxygen demand.

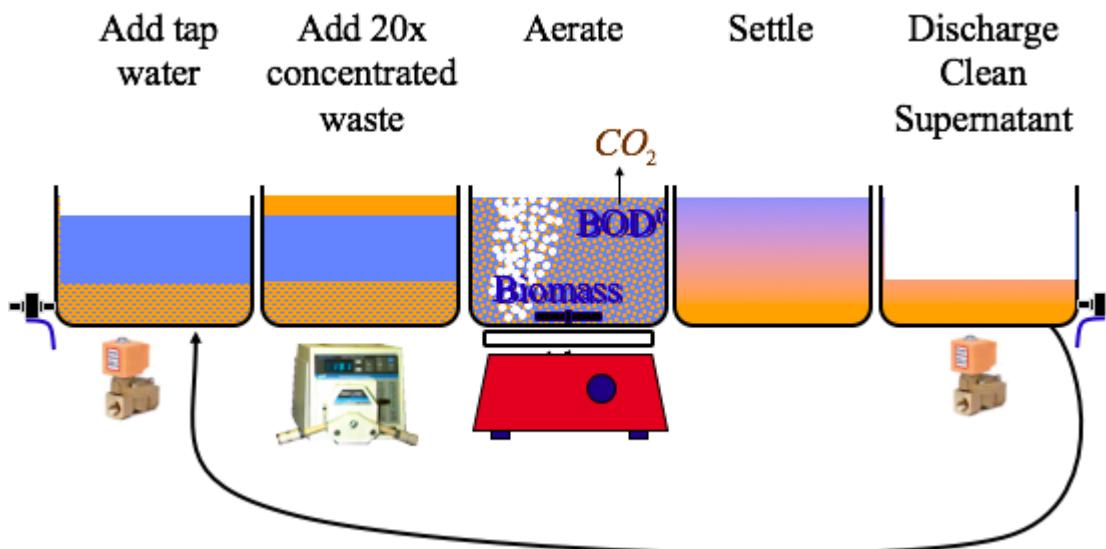


Figure 0. Process diagram of SBRs (Weber-Shirk, 2018)

## Objectives and Hypothesis

The effectiveness of an SBR can be determined by the BOD removal efficiency of the reactor. The BOD removal efficiency will be determined through calculating the difference in DO of the reactor and the influent sludge mixture.

Our hypothesis is that BOD removal will be more efficient with lower air flow rates. While we predict that the total amount of O<sub>2</sub> transferred into the reactor will be greater with higher air flow rates, we believe that the higher air flow rates will result in an overall lower BOD removal efficiency. This correlates with our findings during

the gas transfer lab, in which we discovered that higher air flow rates resulted in a lower oxygen transfer efficiency.

## Experimental plan

The BOD removal efficiency of the reactor will be determined through calculating the oxygen transfer efficiency (OTE) of the different aeration rates. OTE is calculated as follows:

$$OTE = \frac{\hat{k}_{v,l} (C_{eq} - C) VRT}{MW_{O_2} Q_{air} P_{air} f_{O_2}}$$

Equation 1. Oxygen transfer efficiency equation

Where:

- $\hat{k}_{v,l}$  = volumetric gas transfer coefficient, obtained from interpolation of values from the gas transfer lab. See Figure 1 below

- $\hat{k}_{v,l,400} = 0.029 s^{-1}$

- $\hat{k}_{v,l,200} = 0.02 s^{-1}$

- $\hat{k}_{v,l,100} = 0.013 s^{-1}$

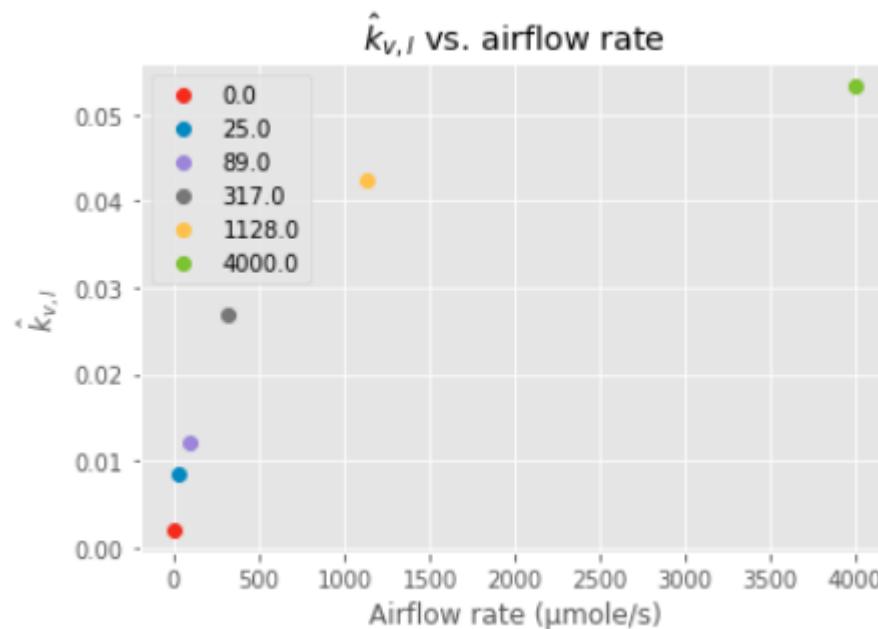


Figure 1.  $\hat{k}_{v,l}$  values from Lab 6

- $C_{eq}$  = saturation concentration of DO = 8.76 mg/L
- C = concentration of DO in mg/L
- V = volume of the reactor = 0.5 L
- R = ideal gas constant = 8.314 J/(K\*mol)
- T = room temperature in Kelvin
- $MW_{O_2}$  = molecular weight of oxygen in mg (32000 mg/mol)
- $Q_{air}$  = Flow rate (varied for experiment)
- $P_{air}$  = Standard atmospheric pressure = 101.325 kPa
- $f_{O_2}$  = fraction of O<sub>2</sub> in atmosphere = 0.21

Using the OTE, the amount of oxygen transferred into the reactor will be calculated by the following:

$$O_2 \text{ Transferred} = OTE * \text{timeinterval} * \text{FlowRate}$$

Equation 2. Oxygen transfer equation

Where:

- Time interval = interval of ProCoDA measurements (5 seconds)
- Flow rates = 400, 200, 100  $\mu\text{mol/s}$

The BOD removal efficiency will be determined with the following equation:

$$\text{efficiency}_{100} = \frac{1 - (BOD_{influent} - O_{2_{100}})}{BOD_{influent}}$$

$$BOD Removal Efficiency = \left( \frac{1 - (BOD_{feed} - O_2 \text{ Transferred})}{BOD_{feed}} \right) * 100$$

Equation 3. BOD removal efficiency

Note that the oxygen deficit during the data interval (5 seconds) is constant. (i.e., DO at time t = 0 applies for t = 0 through t = 5, DO at time t = 5 applies for t = 5 through t = 10)

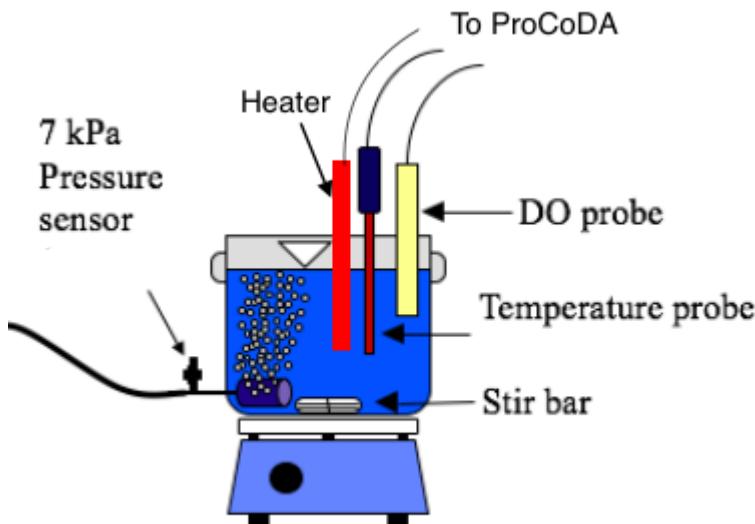


Figure 2. Experimental setup of the SBR (Monroe, 2018)

Flow rates: 400, 200, 100  $\mu\text{mol/s}$

## Key design parameters

Variable	Value/Type
Batch reactor volume	0.5 L
Type of influent pollutant	Completely soluble at feed concentration, 325 mg/L COD (Chemical Oxygen Demand), 40.9 mg/L nitrogen (for more information regarding exact composition of feed solution, see Figure 3)
Concentration of influent pollutant	10% of Stock 1 + 1% of Stock 2 + 1% of Stock 3
Sludge volume	0.2 L

Variable	Value/Type
Influent pollutant volume	0.2 L

Table 1. Key design parameters table

	Chemical Compound	Molecular Weight g/mol	Concentration mg/L
<b>Stock 1 (100x) refrigerator</b>	Starch	~40,000	84.40
	Casein	~30,000	125.00
<b>Organic carbon</b>	Sodium acetate	C <sub>2</sub> H <sub>3</sub> O <sub>2</sub> Na·3H <sub>2</sub> O	136.1
	Capric acid	C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	172.3
<b>Nitrogen</b>	Ammonium chloride	NH <sub>4</sub> Cl	53.5
<b>Phosphate and pH</b>	Potassium phosphate	K <sub>2</sub> HPO <sub>4</sub>	174.2
	Sodium hydroxide	NaOH	40.0
	Glycerol	C <sub>3</sub> H <sub>8</sub> O <sub>3</sub>	92.1
<b>Stock 2 1000x</b>	Magnesium sulfate	MgSO <sub>4</sub> ·7H <sub>2</sub> O	246.5
<b>Metals</b>	Sodium molybdate	NaMoO <sub>4</sub> ·2H <sub>2</sub> O	241.9
	Manganese sulfate	MnSO <sub>4</sub> ·H <sub>2</sub> O	169.0
	Cupric sulfate	CuSO <sub>4</sub> ·4H <sub>2</sub> O	249.7
	Zinc sulfate	ZnSO <sub>4</sub> ·7H <sub>2</sub> O	287.5
<b>Stock 3 1000x</b>	Calcium chloride	CaCl <sub>2</sub> ·2H <sub>2</sub> O	147.0
	Iron chloride	FeCl <sub>3</sub> ·6H <sub>2</sub> O	270.3
	Cobalt chloride	CoCl <sub>2</sub> ·6H <sub>2</sub> O	237.9

Figure 3. Synthetic Feed Composition

## Procedure

### Part A - Setting Up

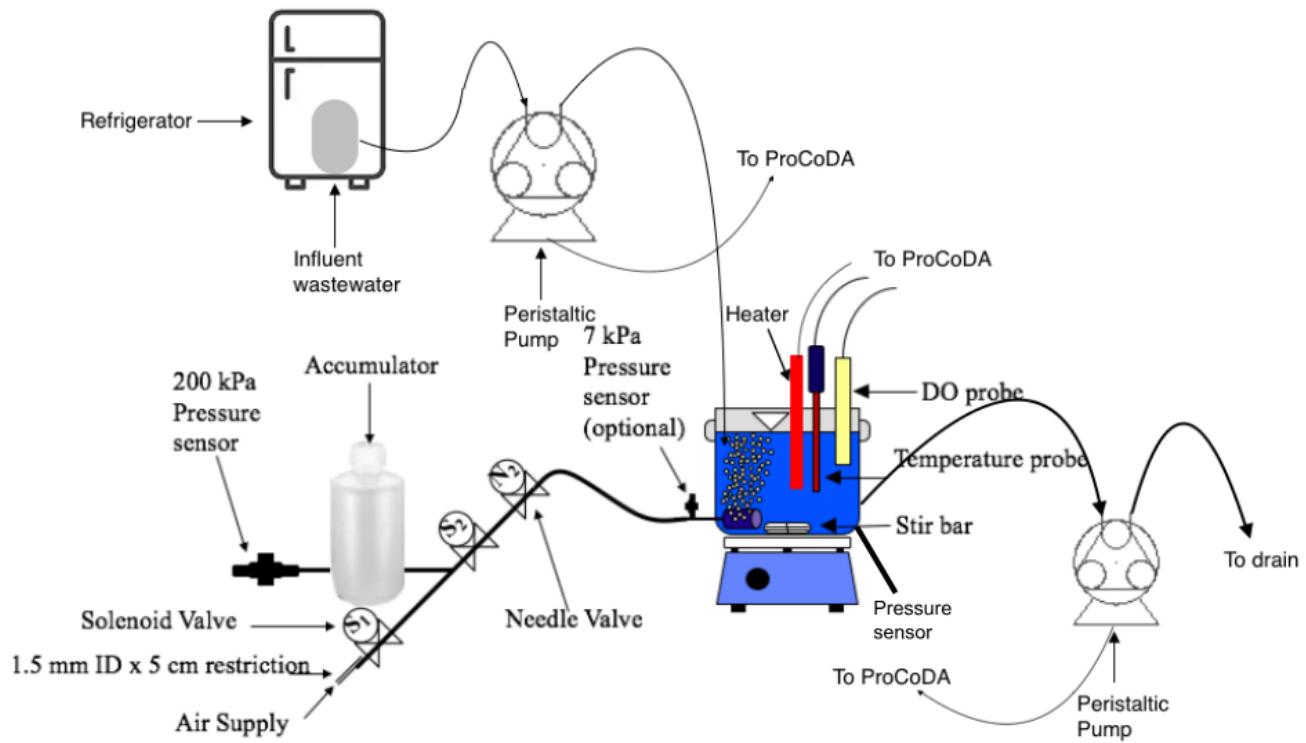


Figure 4. Schematic of setup, adapted from (Weber-Shirk, 2018)

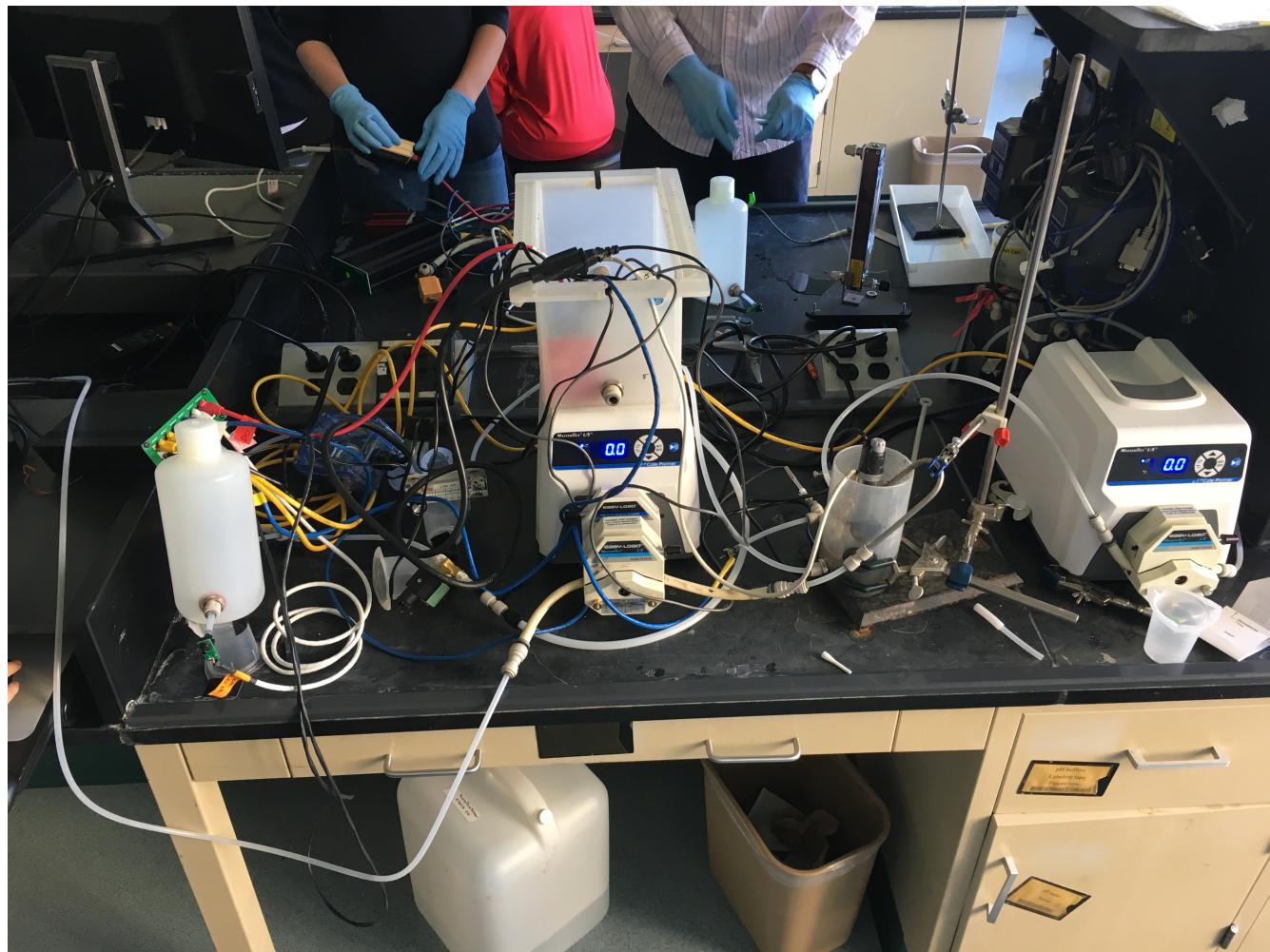


Figure 5. Picture of setup

1. Assemble the lab setup according to the schematic in Figure 4 and the picture in Figure 5.

a. Connect peristaltic pump (influent). The tubing should come from the synthetic feed which is stored in the refrigerator and go to the inlet of the batch reactor. The tubing going into the reactor and coming out of the refrigerator should be 3/8" while the tubing clamped by the peristaltic pump should be #17 tubing.

b. Connect peristaltic pump (effluent). The tubing should come from the effluent outlet indicated in Figure 6 and go to the drainage. The tubing coming in and out of the reactor and into the drain should be 3/8" tubing while the tubing clamped by the peristaltic pump should be #17 tubing.

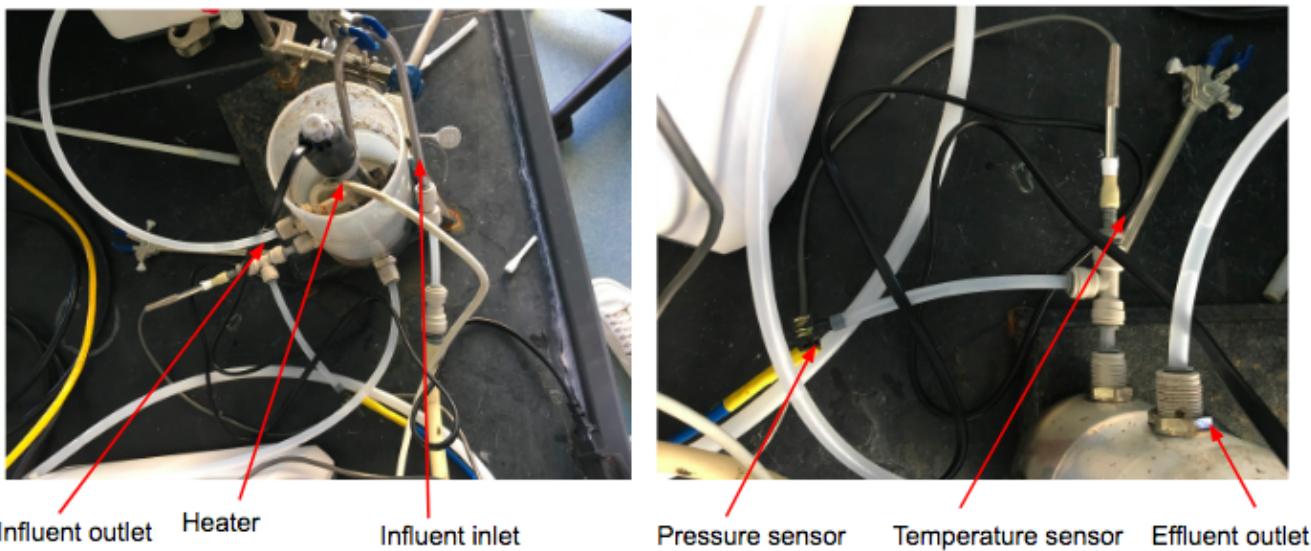


Figure 6. Batch Reactor Setup

2. Test the air flow controller and calibrate the DO probe according to the steps in the Lab 6: Gas Transfer manual.
3. Assemble the batch reactor according to the photo in Figure 6. Ensure that the effluent outlet does not extend too far into the batch reactor to prevent unnecessary removal of sludge.
4. Create the synthetic feed solution. Dilute the solution to 10% of its original concentration. Add 20 mL of the concentrated solution into 180 mL of regular tap water
5. Plug the pressure sensors, valves, heater and pumps into the ProCoDA interface using the following scheme:

Port	Device	Purpose
Pump 0	Peristaltic pump (Influent)	For pumping in the synthetic feed solution into the reactor
Pump 1	Peristaltic pump (Effluent)	For pumping out settled waste from reactor into drain
Sensor 0	200 kPa Pressure sensor (accumulator)	For measuring the airflow rate of air into reactor
Sensor 1	7 kPa Pressure sensor (batch reactor)	To sense the water depth of the reactor
Sensor 2	DO Probe	For measuring DO of reactor
Sensor 3	Temperature Sensor	For reading temperature of sludge+feed solution
24v2	Solenoid valve 1	For controlling the airflow rate of air into reactor
24v3	Solenoid valve 2	For controlling the airflow rate of air into accumulator
24v4	Heater	For preventing sludge from contacting feed solution that is too cold

Table 2. ProCoDA interface connections

## Part B - ProCoDA Steps and Rules

1. Enter the following steps and rules into ProCoDA

Step	Processes during step	Rule for going to next step

Step	Processes during step	Rule for going to next step
Pump (Fill) 1	Turn on first peristaltic pump to retrieve wastewater influent at a rate of 380 mL/min	Waste height reaches 8 cm
Heating 1	Turn on heater to heat up reactor	Reactor reaches room temperature
Pre-setting 1	None	15 minutes pass
Aeration height (Drain) 1	Turn on second peristaltic pump to drain out waste	Waste height reaches 5.5 cm
Aerate 1	Turn on the air valve to have air flow into the reactor at a rate of 400 $\mu\text{M}/\text{s}$	4 hours pass
Settling 1	None	15 minutes pass
Pump (Drain) 1	Turn on second peristaltic pump to drain out waste	Waste height reaches practically 0
Pump (Fill) 2	Turn on first peristaltic pump to retrieve wastewater influent at a rate of 380 mL/min	Waste height reaches 8 cm
Heating 2	Turn on heater to heat up reactor	Reactor reaches room temperature
Pre-setting 2	None	15 minutes pass

Step	Processes during step	Rule for going to next step
Aeration height (Drain) 2	Turn on second peristaltic pump to drain out waste	Waste height reaches 5.5 cm
Aerate 2	Turn on the air valve to have air flow into the reactor at a rate of 200 $\mu\text{M}/\text{s}$	4 hours pass
Settling 2	None	15 minutes pass
Pump (Drain) 2	Turn on second peristaltic pump to drain out waste	Waste height reaches practically 0
Pump (Fill) 3	Turn on first peristaltic pump to retrieve wastewater influent at a rate of 380 mL/min	Waste height reaches 8 cm
Heating 3	Turn on heater to heat up reactor	Reactor reaches room temperature
Pre-setting 3	None	15 minutes pass
Aeration height (Drain) 3	Turn on second peristaltic pump to drain out waste	Waste height reaches 5.5 cm
Aerate 3	Turn on the air valve to have air flow into the reactor at a rate of 400 $\mu\text{M}/\text{s}$	4 hours pass
Settling 3	None	15 minutes pass

Step	Processes during step	Rule for going to next step
Pump (Drain) 3	Turn on second peristaltic pump to drain out waste	Waste height reaches practically 0
Off		

Table 3. Process flow table for SBR

# Results

## DO Over Time

```

data_file_path = '/Users/Jonathan/github/CEE-4530-jct259-/CEE4530/Final Lab/flow_rate.csv'
firstrow_400 = 2
lastrow_400 = 3107 #column size was determined through visual inspection in Excel
time_data_400 = EPA.ftime(data_file_path, firstrow_400, lastrow_400)
DO_column_400 = EPA.Column_of_data(data_file_path, firstrow_400, lastrow_400, 4, 'r')
AVG_400=np.average(DO_column_400) #average DO of the 400umol/s airflow
AVG_400

firstrow_200 = 3810
lastrow_200 = 6915
time_data_200 = EPA.ftime(data_file_path, firstrow_200, lastrow_200)
DO_column_200 = EPA.Column_of_data(data_file_path, firstrow_200, lastrow_200, 4, 'r')
AVG_200=np.average(DO_column_200)
AVG_200

firstrow_100 = 7368
lastrow_100 = 10473
time_data_100 = EPA.ftime(data_file_path, firstrow_100, lastrow_100)
DO_column_100 = EPA.Column_of_data(data_file_path, firstrow_100, lastrow_100, 4, 'r')
AVG_100=np.average(DO_column_100)
AVG_100

plt.plot(time_data_400, DO_column_400, label='400$\mu$mol/s')
plt.plot(time_data_200, DO_column_200, label='200$\mu$umol/s')
plt.plot(time_data_100, DO_column_100, label='100$\mu$umol/s')

```

```

plt.title('Dissolved Oxygen concentration vs. time')
plt.xlabel(r'$time (day)$')
plt.ylabel(r'${\text{Oxygen concentration}} \left( \frac{\text{mg}}{\text{L}} \right)$')
plt.legend()

plt.show()

```

## Calculating OTE

```

f_02 = 0.21 #fraction of O2 in atmosphere
MW_02 = 32000*u.mg/u.mol #molecular weight of O2 in mg
C_star = 8.76*u.mg/u.L #saturation DO of solution determined with DO probe
Q_400 = 400*u.umol/u.s
Q_200 = 200*u.umol/u.s
Q_100 = 100*u.umol/u.s
R = 8.314*u.J/u.K/u.mol
temp = 294*u.K #room temperature
volume=0.5*u.L
pressure=101.325*u.kPa

k_vl_400=1/0.029*u.s #kvl values were determined using interpolation of kvl graphs
k_vl_200=1/0.02*u.s
k_vl_100=1/0.013*u.s

OTE_400=((volume*k_vl_400*(C_star-DO_column_400)*R*temp)/(f_02*Q_400*MW_02*pressure)
OTE_200=((volume*k_vl_200*(C_star-DO_column_200)*R*temp)/(f_02*Q_200*MW_02*pressure)
OTE_100=((volume*k_vl_100*(C_star-DO_column_100)*R*temp)/(f_02*Q_100*MW_02*pressure)

OTE_400_AVG=np.average(OTE_400)
OTE_400_AVG
OTE_200_AVG=np.average(OTE_200)
OTE_200_AVG
OTE_100_AVG=np.average(OTE_100)
OTE_100_AVG

plt.plot(time_data_400, OTE_400, label = '400$\mu$mol/s')
plt.plot(time_data_200, OTE_200, label = '200$\mu$mol/s')
plt.plot(time_data_100, OTE_100, label = '100$\mu$mol/s')

plt.title('OTE vs. time')
plt.xlabel('time (day)')
plt.ylabel('OTE')
plt.legend()

plt.show()

```

# Oxygen Transferred

```

time_int=5*u.s
O2_bubbled_400=Q_400*time_int*OTE_400 #please refer to Equation 2 in Experimental I
O2_bubbled_200=Q_400*time_int*OTE_200
O2_bubbled_100=Q_400*time_int*OTE_100

oxygen_transferred_400=np.sum(O2_bubbled_400)
oxygen_transferred_400 #determining total mass of oxygen bubbled into reactor

oxygen_transferred_200=np.sum(O2_bubbled_200)
oxygen_transferred_200
oxygen_transferred_100=np.sum(O2_bubbled_100)
oxygen_transferred_100

plt.plot(time_data_400, O2_bubbled_400, label = '400$\mu$mol/s')
plt.plot(time_data_200, O2_bubbled_200, label = '200$\mu$mol/s')
plt.plot(time_data_100, O2_bubbled_100, label = '100$\mu$mol/s')

plt.title('Oxygen Transferred vs. time')
plt.xlabel('time (day)')
plt.ylabel(r'Oxygen Tranferred (mg)')
plt.legend()

plt.show()

```

# BOD Removal Efficiency

```

BOD_influent = 65000 #A known amount determined by multiplying the known BOD of the
O2_400= 646.35
O2_200= 6232.43
O2_100=70967.25

efficiency_400= (1-(BOD_influent-O2_400)/BOD_influent)*100
efficiency_400 #see Equation 3 in Experimental Plan section

efficiency_200= (1-(BOD_influent-O2_200)/BOD_influent)*100
efficiency_200

efficiency_100= (1-(BOD_influent-O2_100)/BOD_influent)*100
efficiency_100

if(efficiency_100>100):
    efficiency_100=100

air_flows= [100,200,400]
efficiencies = [efficiency_400,efficiency_200,efficiency_100]

```

```

plt.plot(air_flows, efficiencies, 'ro')

plt.title('BOD Removal Efficiency vs Flow Rate')
plt.xlabel('Flow Rate ($\mu$mol/s)')
plt.ylabel('BOD Removal Efficiency')

plt.show()

```

# Results

Airflow Rate ( $\mu\text{mol/s}$ )	Average DO (mg/L)	Average OTE	Average O <sub>2</sub> Tranferred (mg/L)	BOD Removal Efficiency (%)
100	0.4831	0.011428	70967.25	109.18
200	6.5233	0.001004	6232.43	9.59
400	8.0873	0.000104	646.35	0.99

Table 4. Results for various airflow rates

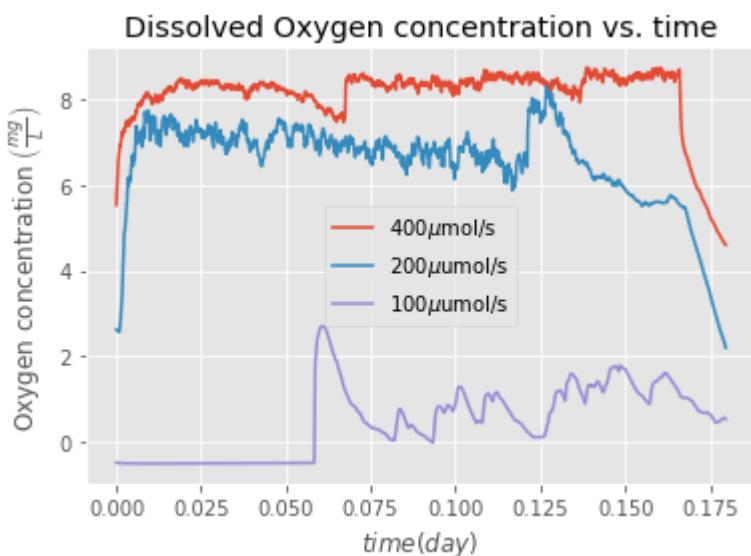


Figure 7. DO vs time

In Figure 7, it becomes apparent that a higher rate of bubbling translates to a higher dissolved oxygen level (D.O. in mg/L) for each of the cycles. The 400  $\mu\text{M}/\text{s}$ , 200  $\mu\text{M}/\text{s}$ , and 100  $\mu\text{M}/\text{s}$  cycles (each for a duration of 4 hours) exhibited average D.O. levels of 8.08 mg/L, 6.52 mg/L, and 0.48\* mg/L, respectively. It is important to note that D.O. levels were used in the transient calculation of the oxygen transferred (they represent the deficit section of the transfer efficiency equation) but the general trend still holds that higher bubbling rates results in higher D.O. levels of the reactant solution. However, further inspection reveals that this higher D.O. lowers the efficiency of the system by allowing less oxygen to be effectively transferred to solution.

Further trials reveal that varying aeration times yields little to no difference in D.O over time. This bolsters our experimental assumption that the D.O of the reacting solution (in this case a mixture of aerobic sludge, water, and synthetic solution) is directly dependent on the aeration rate and not the length of aeration. However, total oxygen transferred does depend on interval and rate of aeration.

*It is important to note that the third trial in our experiment yielded DO data that was mostly 0 during the first period of the aeration. We suspect that this is because the settling of the sludge from the previous cycle encapsulated the DO probe and the aeration rate was not high enough to remove the sludge.*

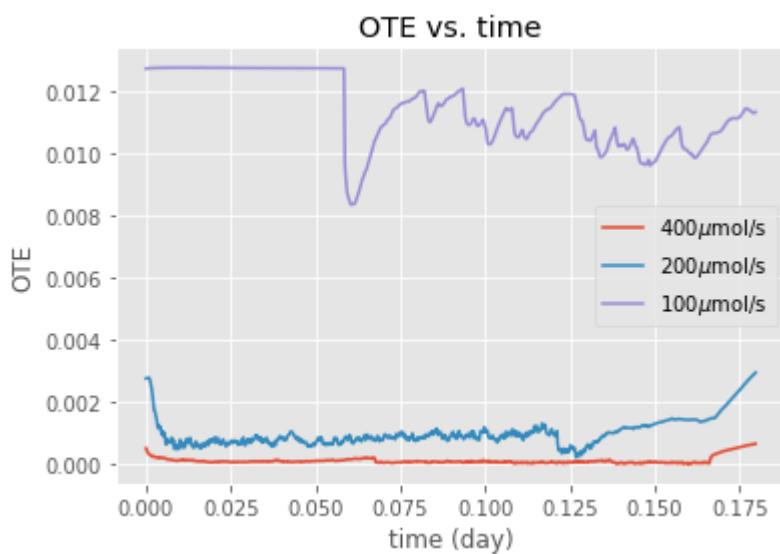


Figure 8. OTE vs time

In Figure 8, OTE shows an interesting inverse relationship to D.O. – a higher airflow rate results in a significantly lower OTE. Utilizing our experimentally derived  $\hat{k}_{v,l}$

values from our previous experiments and the deficit acquired from a transient block-average analysis of Figure 7, we achieved a completed picture of the OTE trend for our various flowrates. The efficiency of the 400  $\mu\text{M}/\text{s}$  and 200  $\mu\text{M}/\text{s}$  trials hover around 0.00010 to 0.00100, respectively, with the superior flow rate of 100  $\mu\text{M}/\text{s}$  exhibiting an average efficiency of 0.01142. This is due to the intrinsic dependency of the reactant solutions' dissolved oxygen level and aeration rate, revealing a propensity to assimilate more oxygen under lower flow rates (i.e., effectively a higher percentage of the oxygen bubbles for the lower flow rates are assimilated into solution as opposed to the higher flow rates). This trend lends to the next assumption regarding oxygen transfer.

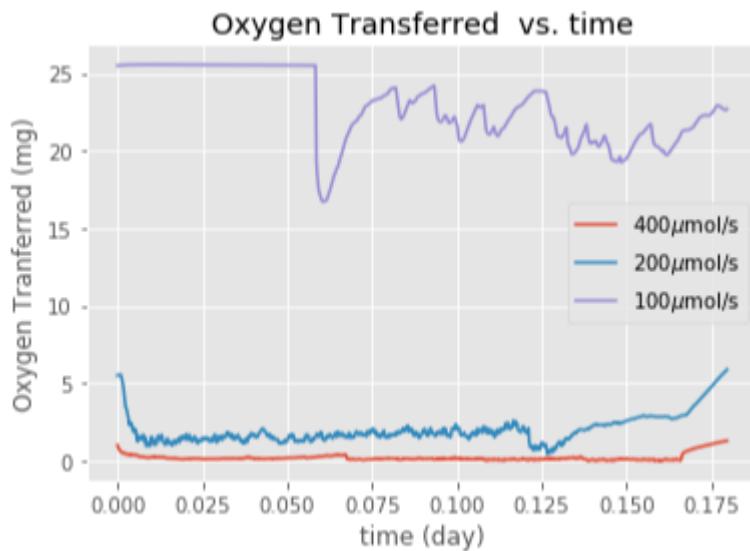


Figure 9.  $\text{O}_2$  Transferred (delta t intervals -mg ) vs Time

Interestingly, the integral and interval side-by-side (Figure 9) analysis of  $\text{O}_2$  transfer reveals the superiority of the lower flow rate. This goes against initial assumptions that a higher flow rate would lead to more oxygen being transferred; however, antagonistic mechanisms (such as the saturation of solution) lead to the  $\text{O}_2$  trend pictured.  $\text{O}_2$  is presented as a trend when in actuality the calculation for our point is the interval sum (over delta t) – the respective summation of these array elements leads to a total  $\text{O}_2$  transferred value. The 400  $\mu\text{M}/\text{s}$ , 200  $\mu\text{M}/\text{s}$ , and 100  $\mu\text{M}/\text{s}$  experiments attributed 646.35 mg, 6232.43 mg, and 70967.25 mg of oxygen, respectively (Table 3).

The graph of these points is representative of the  $\text{O}_2$  transferred over interval (i.e. element(i) of array is the representative mg of  $\text{O}_2$  transferred during the 5 second time interval)

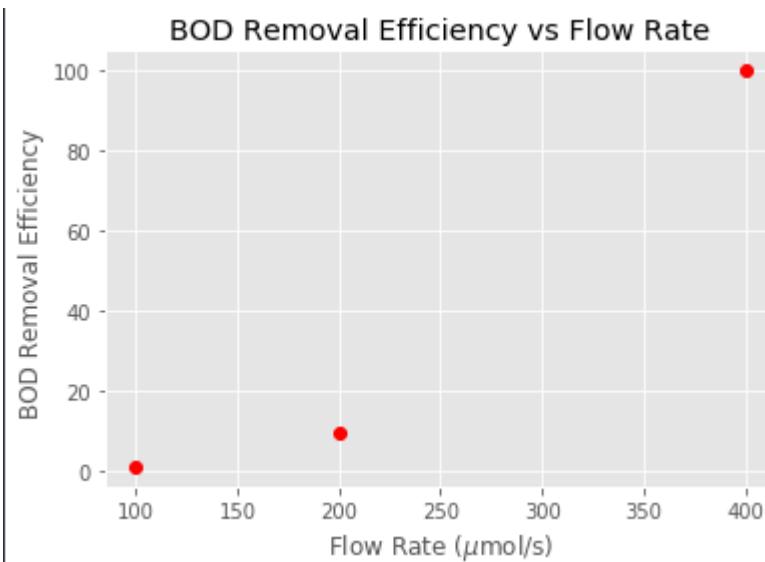


Figure 10. Evaluation of BOD Removal Efficiency

This experiment aimed to offer a practical view on wastewater treatment and the most effective way to remove sample BOD. The known BOD of our 200 mL sample (each trial presented the same BOD approximation) was 325 mg/L presenting a total O<sub>2</sub> demand of 65,000 mg. The first experiment (with cycles a function of air flow rates) revealed a total O<sub>2</sub> transfer of 646.35 mg, 6232.43 mg, and 70967.25 mg for the 400  $\mu\text{M/s}$ , 200  $\mu\text{M/s}$ , and 100  $\mu\text{M/s}$  trials, respectively. Efficiency is then calculated as a function of BOD with the equation  $(\text{BOD} - \text{O}_2)/\text{BOD}$ . This reveals a BOD removal efficiency of 0.99%, 9.59%, and 100%\* for the 400  $\mu\text{M/s}$ , 200  $\mu\text{M/s}$ , and 100  $\mu\text{M/s}$  trials, respectively.

*Our 100  $\mu\text{M/s}$  trial effectively transferred more O<sub>2</sub> than is required by our sludge into the solution, removing 100%+ of the demand in the solution. Iteration in length of time of aeration for the 100  $\mu\text{M/s}$  cycle should be investigated.*

## Conclusion

Our recommendation to a wastewater facility would be to keep DO below 2-3 mg/L due to the greatly enhanced oxygen transfer properties that this offers. Additionally, bubbling rates should not exceed 100-200  $\mu\text{M/s}$  for maximal O<sub>2</sub> transfer into solution. A sequence batch reactor with a DO gauge to monitor time-averaged DO as well as a frequent low bubbling (<200  $\mu\text{M/s}$ , ideally around 100  $\mu\text{M/s}$ ) can be used to successfully treat wastewater and remove the BOD before discharge.

Further experimentation and iteration would focus on the length of time of aeration for the best efficiency flow rate as to further make the process more efficient (real-time analysis of cumulative O<sub>2</sub> transferred allows for adjustments to the process as to achieve 100% by end of cycle with no significant over-expenditure of energy).

## Issues and Suggestions

Issues	Suggestion
Spillage of sludge and wastewater on to benchtop	Use larger volume batch reactor, fit tray underneath reactor
Sludge remaining in reactor between cycles too low	Increase settling time to minimize concentration of sludge in effluent
Unsure of accuracy and repeatability of trials	Try BOD removal efficiency of different organisms
DO reading for cycle 3 of experiment was compromised due to buildup of sludge (by settling) and lack of turbulence to free DO probe	Installing some sort of rotating drum or shaking mechanism to induce turbulence without having to resort to a higher, less-efficient air flow rate. Alternatively, a smart configuration for the DO probe which avoids the effects of sludge settling/blocking would be recommended.

Table 4. Issues and improvements table