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APPENDICES

APPENDIX A

TOTAL INORGANIC CARBON ANALYSE EXPERIMENTAL DATA

Table A-1 $\%CO_2$ dissolution efficiencies at different time at different pH value 6, 8 and 10 in 1 m high bubble column

(a) At pH 6

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	47.31	56.05	4.54	44.10
30	74.49	91.70	6.72	79.24
45	102.37	130.64	6.31	106.83
60	130.77	157.44	1.75	129.53

(b) pH 8

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	56.05	88.21	21.09	70.97
30	91.70	100.10	4.29	94.74
45	130.64	143.90	7.73	136.11
60	157.44	168.50	6.17	161.81

(c) At pH 10

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	92.85	86.53	4.47	89.69
30	126.00	138.72	8.99	132.36
45	154.10	163.92	6.94	159.01
60	182.50	188.02	3.90	185.26

Table A-2 $\%CO_2$ dissolution efficiencies at different time at different pH 6, 8 and 10 in 1 m high packed column

(a) At pH 6 (at top and middle of the column)

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	44.21	46.69	1.75	45.45
30	129.61	127.22	1.69	129.25
45	219.41	190.02	20.78	205.55
60	277.31	257.82	13.78	268.40

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	93.26	133.61	23.60	113.43
30	143.26	157.11	8.31	150.18
45	220.96	186.01	19.88	203.48
60	224.66	220.11	2.36	222.38

(b) At pH 8 (at top and middle of the column)

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	60.57	57.04	2.34	58.81
30	162.88	142.05	14.57	152.47
45	248.64	226.52	15.49	237.58
60	287.84	285.32	1.63	286.58

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	102.03	110.43	5.51	106.23
30	141.83	144.13	2.10	142.98
45	201.83	204.13	2.10	202.98
60	240.23	214.33	14.38	227.28

(c) At pH 10 (at top and middle of the column)

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	132.19	117.11	10.54	124.65
30	204.79	197.21	5.23	201.00
45	276.99	264.51	8.70	270.75
60	340.49	302.61	26.66	321.55

Time (min)	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
	1st time	2nd time	SD	Avg
15	144.83	135.34	5.00	140.09
30	192.43	189.24	1.56	190.84
45	240.13	243.24	2.52	241.69
60	261.33	251.64	5.11	256.49

Table A-3 %CO_2 dissolution efficiencies at different time and height in 3 m high packed column

(a) At 1m

Time (min)	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
	1st time	2nd time	SD	Avg
15	54.41	66.83	8.78	60.62
30	257.13	272.53	10.89	264.83
45	297.03	300.53	2.47	298.78
60	311.13	309.63	1.06	310.38

(b) At 2m

Time (min)	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
	1st time	2nd time	SD	Avg
15	29.47	28.69	0.27	29.08
30	153.68	122.43	11.05	138.06
45	231.18	205.63	9.03	218.41
60	274.68	232.53	14.90	253.61

(c) At 3m

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	19.84	16.84	1.06	18.34
30	52.95	58.76	2.05	55.85
45	142.36	172.12	10.52	157.24
60	180.91	197.52	5.87	189.21

Table A-4 $\%CO_2$ dissolution efficiencies at different time and flowrate in range 10-40 $cc \cdot min^{-1}$ in 1 m high bubble column

(a) At 10 $cc \cdot min^{-1}$

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	89.94	86.31	0.39	88.12
30	123.09	138.50	5.42	130.79
45	151.19	163.70	2.32	157.44
60	179.59	187.80	3.07	183.69

(b) At 20 $cc \cdot min^{-1}$

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	33.02	36.89	2.73	34.96
30	76.20	66.69	6.73	71.45
45	124.49	135.99	8.13	130.24
60	142.69	147.49	3.39	145.09

(c) At 30 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1}			
(min)	1st time	2nd time	SD	Avg
15	52.32	51.80	0.37	52.06
30	104.69	97.40	5.16	101.04
45	164.99	167.30	1.63	166.14
60	212.99	203.50	6.71	208.24

(d) At 40 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	67.00	67.66	0.47	67.33
30	149.33	149.80	0.33	149.57
45	194.79	177.10	12.51	185.94
60	233.09	203.60	20.85	218.34

Table A-5 (a) %CO_2 dissolution efficiencies at different time and flowrate in range 10-40 cc·min^{-1}in 2 m high bubble column (Samples collected at 1 m position)

(a.1) At 10 cc/min

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	65.19	68.53	2.36	66.86
30	128.34	130.78	1.73	129.56
45	156.44	152.92	2.49	154.68
60	184.84	180.02	3.41	182.43

(a.2) At 20 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	48.61	43.35	3.72	45.98
30	124.18	130.13	4.21	127.15
45	157.29	160.88	2.54	159.08
60	186.94	194.05	5.03	190.49

(a.3) At 30 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	50.74	46.09	3.29	48.41
30	116.99	130.12	9.28	123.55
45	182.59	182.86	0.19	182.72
60	227.69	234.22	4.61	230.95

(a.4) At 40 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	74.75	74.91	0.11	74.83
30	124.95	132.78	5.54	128.87
45	189.15	175.68	9.53	182.42
60	268.85	259.42	6.67	264.14

Table A-5 (b) $\%CO_2$ dissolution efficiencies at different time and flowrate in range 10-40 cc/min in 2 m high bubble column (Samples collected at 2 m position)

(b.1) At 10 $cc \cdot min^{-1}$

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	9.08	8.53	0.39	8.81
30	48.39	40.72	5.42	44.55
45	102.64	105.92	2.32	104.28
60	135.68	140.02	3.07	137.85

(b.2) At 20 $cc \cdot min^{-1}$

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	13.02	16.69	2.59	14.86
30	76.20	66.69	6.73	71.45
45	124.49	135.99	8.13	130.24
60	210.69	197.49	9.34	204.09

(b.3) At 30 $cc \cdot min^{-1}$

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	42.32	41.80	0.37	42.06
30	144.69	137.40	5.16	141.04
45	174.79	167.10	5.44	170.94
60	233.09	213.60	13.78	223.34

(b.4) At 40 cc·min^{-1}

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	124.23	109.53	10.39	127.80
30	184.73	173.66	7.83	190.12
45	213.93	194.13	14.00	214.95
60	250.83	227.53	16.48	250.10

Table A-6 % CO_2 dissolution efficiencies at different time and salinity

(a) At 5 ppt salinity

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	51.57	52.45	7.22	61.78
30	86.83	88.77	7.59	97.57
45	107.43	103.37	5.47	115.17
60	127.13	136.67	10.28	141.67

(b) At 10 ppt salinity

Time	Total Inorganic Carbon (mg·L^{-1})			
(min)	1st time	2nd time	SD	Avg
15	23.59	29.39	10.26	38.11
30	46.14	50.96	9.92	60.17
45	72.86	74.07	8.64	85.08
60	99.77	103.72	9.61	113.36

(c) At 30 ppt salinity

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	18.18	18.06	4.67	24.79
30	45.28	46.93	5.30	52.77
45	66.21	72.87	7.07	76.21
60	93.47	101.18	7.44	103.99

Table A-7 $\%CO_2$ dissolution efficiencies at different time and recycle flowrate using C.C.C.

(a) At 1 LPM recycle flowrate

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	17.20	27.43	7.24	22.32
30	22.97	33.87	7.71	28.42
45	49.47	48.71	0.53	49.09
60	58.61	65.26	4.70	61.94

(b) At 2 LPM recycle flowrate

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$			
(min)	1st time	2nd time	SD	Avg
15	33.38	33.19	0.13	33.28
30	53.08	46.88	4.38	49.98
45	66.63	64.92	1.21	65.77
60	82.06	82.89	0.59	82.47

(c) At 3LPM recycle flowrate

Time	Total Inorganic Carbon ($mg \cdot L^{-1}$)			
(min)	1st time	2nd time	SD	Avg
15	12.92	12.51	0.29	12.72
30	23.35	30.84	5.30	27.10
45	37.87	38.69	0.58	38.28
60	55.02	54.43	0.42	54.73

APPENDIX B

CULTIVATION OF *C. VALGARIS* WITH BICARBONATE

EXPERIMENTAL DATA

Table B-1 *C. vulgaris* cell concentration at different time without pH adjustment and $NaHCO_3$ added (Blank test)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	15	17	1.41	16
48	22	24	1.41	23
72	34	37	2.30	35
96	49	52	1.94	51
120	60	63	2.12	62
144	64	67	2.12	65

Table B-2 *C. vulgaris* cell concentration at different time and with 30 ppm NaHCO3 added (initial pH = 6)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	20	19	0.88	13
48	45	43	2.65	37
72	66	65	3.54	66
96	96	100	1.94	98
120	103	108	3.18	110
144	104	108	1.77	115

Table B-3 *C. vulgaris* cell concentration at different time and with 30 ppm $NaHCO_3$ added (initial pH = 7)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	14	13	0.88	13.13
48	35	39	2.65	36.88
72	64	69	3.54	66
96	97	100	1.94	98.38
120	108	113	3.18	110.25
144	114	116	1.77	115

Table B-4 *C. vulgaris* cell concentration at different time and with 30 ppm $NaHCO_3$ added (initial pH = 8)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	18	11	0.88	7
48	30	33	0.35	10
72	51	57	2.12	22
96	66	70	3.18	35
120	70	75	2.83	40
144	72	76	3.01	42

Table B-5 *C. vulgaris* cell concentration at different time and with 30 ppm $NaHCO_3$ added (initial pH = 9)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	8	6	0.88	7
48	10	11	0.35	10
72	24	21	2.12	22
96	37	33	3.18	35
120	42	38	2.83	40
144	44	40	3.01	42

Table B-6 *C. vulgaris* cell concentration at different time and with 80 ppm $NaHCO_3$ added (initial pH = 7)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	14	14	0.35	14
48	31	33	1.24	32
72	67	68	0.71	67
96	97	98	0.18	97
120	109	111	1.06	110
144	117	118	1.24	117

Table B-7 *C. vulgaris* cell concentration at different time and with 200 ppm $NaHCO_3$ added (initial pH = 7)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	18	17	0.53	17
48	35	32	1.94	33
72	62	61	0.71	62
96	94	92	1.59	93
120	108	105	2.47	106
144	117	118	1.06	117

Table B-8 *C. vulgaris* cell concentration at different time and with CO_2 dissolution water (initial pH = 7)

Time	Cell concentration (10^6 cells ml^{-1})			
(h)	1st time	2nd time	SD	Avg
0	1	1	0.00	1
24	13	13	0.18	13
48	51	50	1.24	50
72	76	80	3.01	78
96	103	104	0.88	103
120	120	121	0.88	121
144	124	124	0.00	124

APPENDIX C

SAMPLE CALCULATIONS

C.1 %Efficiency of CO_2 dissolution

% Efficiency can be calculated by using equation (3.2);

$$\%Efficiency = \frac{TIC \times V_L}{(\frac{PQ_g tM_w}{RT})}$$

For example, experiment in section 4.1.3, sample collected at 2 m position in which: P = 1.3 bar, T = 298 K, TIC at 60 min = 253.60 mg·L^{-1}, Volume of liquid (V_L) = 1200 mL, CO_2 flowrate = 10 cc·min^{-1}. Substitute these variables and get %efficiency = 21.67%

C.2 Gas hold up

Gas hold up can be determined from equation (4.3) in Chapter 4:

$$\varepsilon_g = \frac{V_g}{V}$$

Vg can be obtained from increasing in column's volume when CO_2 enter the system.

For 1 m high bubble column; Volume of liquid = 1500 mL and Volume of gas = 178 mL; Substitute in equation (4.3) and obtain $\varepsilon_{g,b} = 0.11$.

For 1 m high packed column; Volume of liquid = 1200 mL and Volume of gas = 270 mL; Substitute in equation (4.3) and obtain $\varepsilon_{g,p} = 0.23$.

C.3 Specific growth rate (μ)

Specific growth rate can be computed by equation (3.3) in Chapter 3:

$$\mu = \frac{\ln(N_2) - \ln(N_1)}{t_2 - t_1}$$

Plot $\ln(N_t)/\ln(N_0)$ vs. $(t-t_0)$ and obtain μ from slope of plotting

Where N_t = Cell concentration at t time (10^6 cells ml^{-1})

N_0 = Cell concentration at the beginning (t_0) (10^6 cells ml^{-1})

t = Sample collected time (h)

t_0 = Time at the beginning of cultivation (h)

It noted that only cell concentration in log phase will be used to calculate for μ. For example, cultivation of *C. vulgaris* at initial pH = 7 gave the μ= 0.045 h^{-1} or 1.080 d^{-1} (Figure C.1)

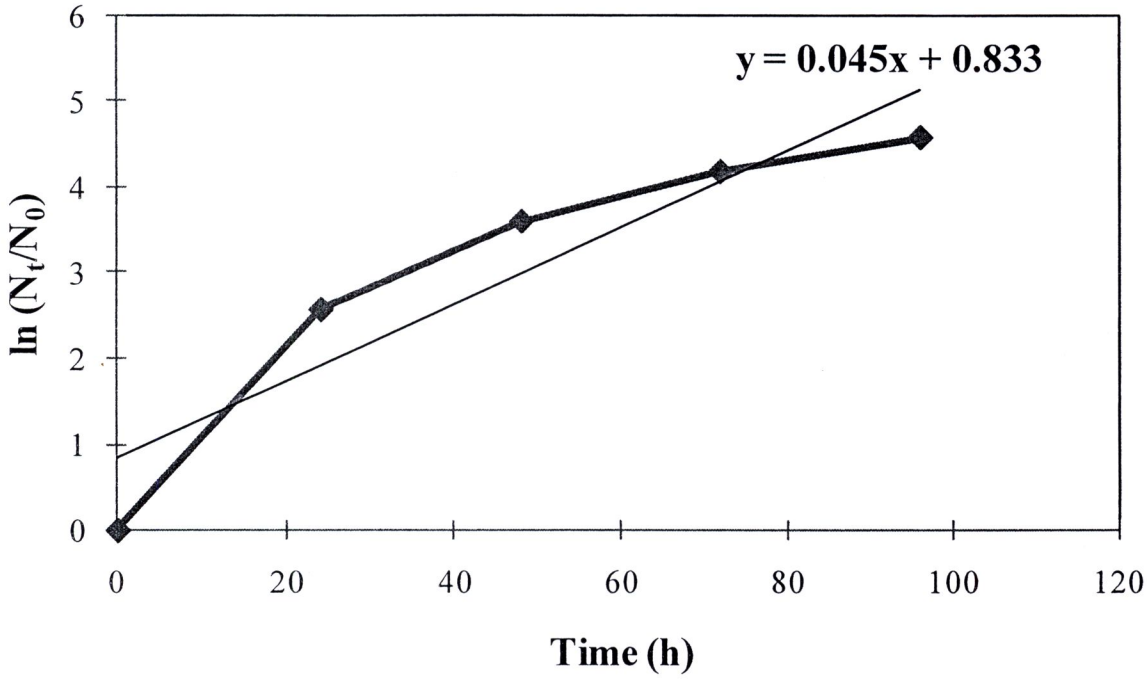

Figure C.1 Plot of $\ln(N_t/N_0)$ vs. Time (h): Determination of μ

C.4 Amount of Sodium Bicarbonate fed into the cultivation system

30 ppm ($mg \cdot L^{-1}$) of $NaHCO_3$ will need 30 mg for 1 L cultivation system

In case of 2.8 L cultivation system will need $NaHCO_3$ $2.8 \times 30 = 84$ mg to be dissolved.

APPENDIX D

PUBLICATIONS

International Symposium / Conference Proceedings

Pichiansoontorn P. and Pavasant P., (2010). ACCELERATING MICROALGAL GROWTH WITH CO_2 TRANSFORMATION. 17th Regional Symposiums on Chemical Engineering (RSCE) Conference Book of Abstract, pp.150, November 22nd-23rd, Bangkok, Thailand

National Symposium / Conference Proceedings

Pichiansoontorn P. and Pavasant P., (2010) Combined Effects of Design and pH-shift for CO_2 absorption in bubble columns. Climate Thailand Conference 2010 proceeding, pp. 567-572, August 19th-20th, Bangkok, Thailand

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