ELECTRONIC SUPPLEMENTARY INFORMATION

The use of bicarbonate for microalgae cultivation and its carbon footprint analysis

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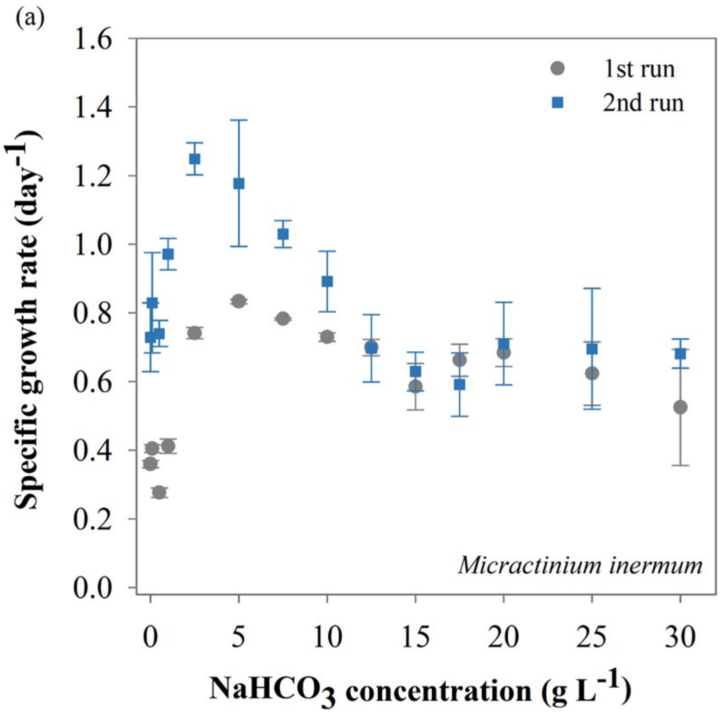
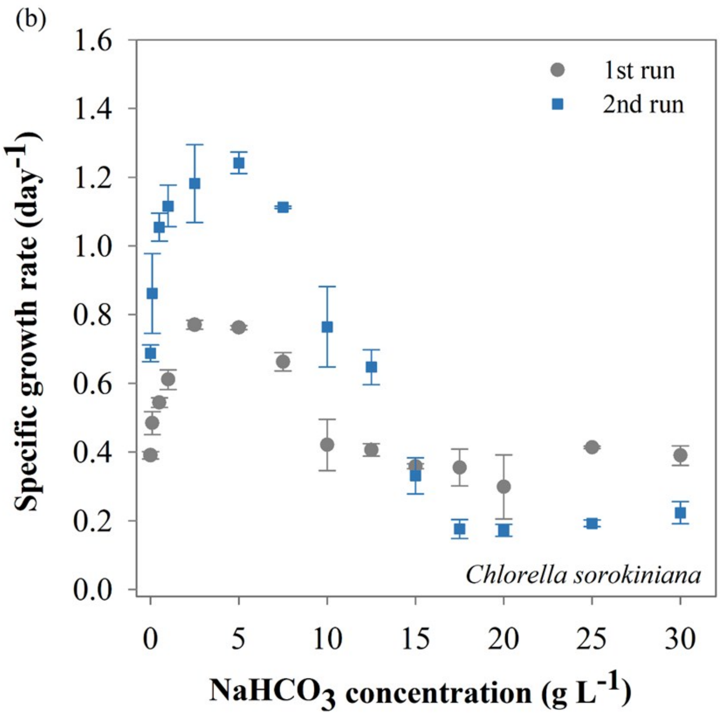
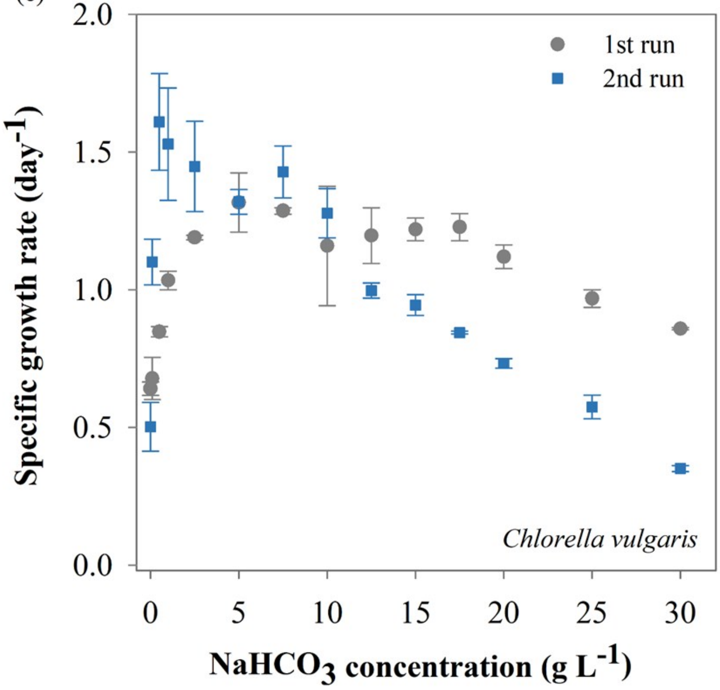
Fig. S1. The specific growth rates of eight algal species with various concentrations of $NaHCO_3$: (a) *Micractinium inermum*; (b) *Chlorella sorokiniana*; (c) *Chlorella vulgaris*; (d) *Scenedesmus* sp.; (e) *Nannochloropsis gaditana*; (f) *Tetraselmis suecica*; (g) *Tetraselmis chuii*; and (h) *Aphanothece* sp.. All values and error bars represent averages and standard deviations, respectively (n = 3).



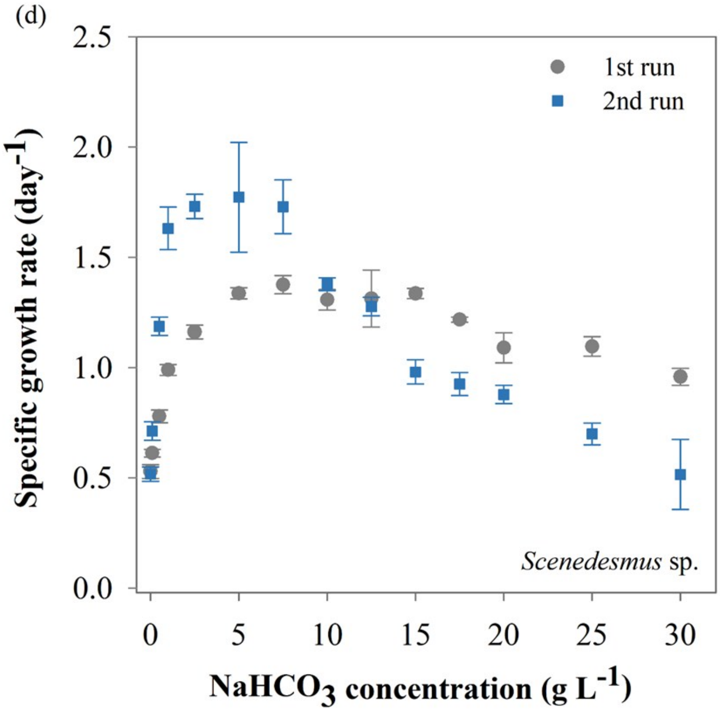


(c)

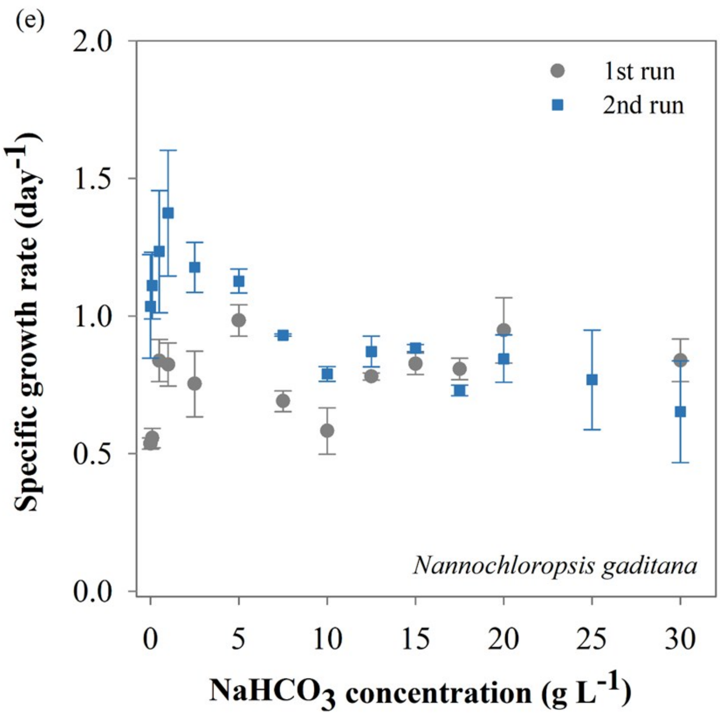


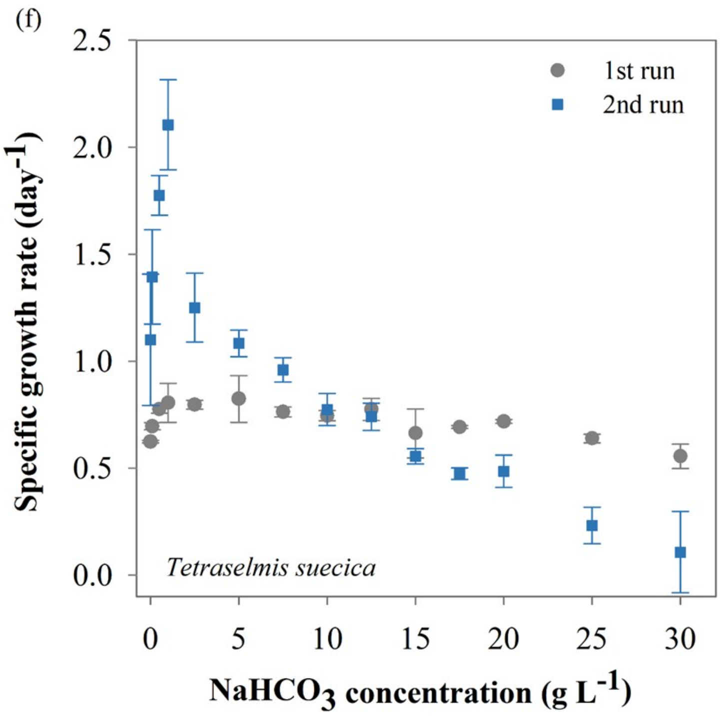
1st run
2nd run
Specific growth rate (day-1)
NaHCO3 concentration (g L-1)
Chlorella vulgaris

(d)



1st run
2nd run
Specific growth rate (day-1)
NaHCO3 concentration (g L-1)
Scenedesmus sp.


(e)
1st run
2nd run
Specific growth rate (day^{-1})
2.0
1.5
1.0
0.5
0.0
Nannochloropsis gaditana
0
5
10
15
20
25
30
NaHCO$_3$ concentration (g L^{-1})


(f)
1st run
2nd run
Specific growth rate (day^{-1})
2.5
2.0
1.5
1.0
0.5
0.0
Tetraselmis suecica
0
5
10
15
20
25
30
NaHCO$_3$ concentration (g L^{-1})

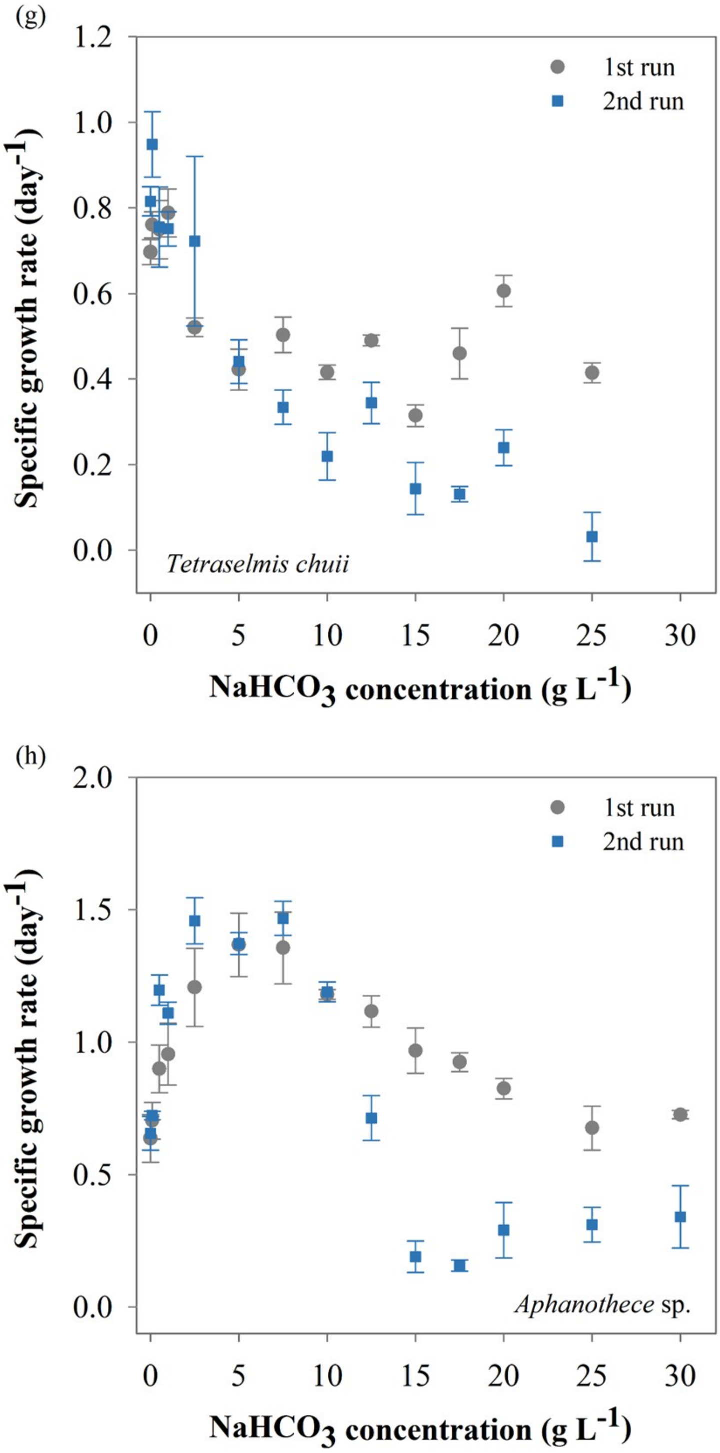
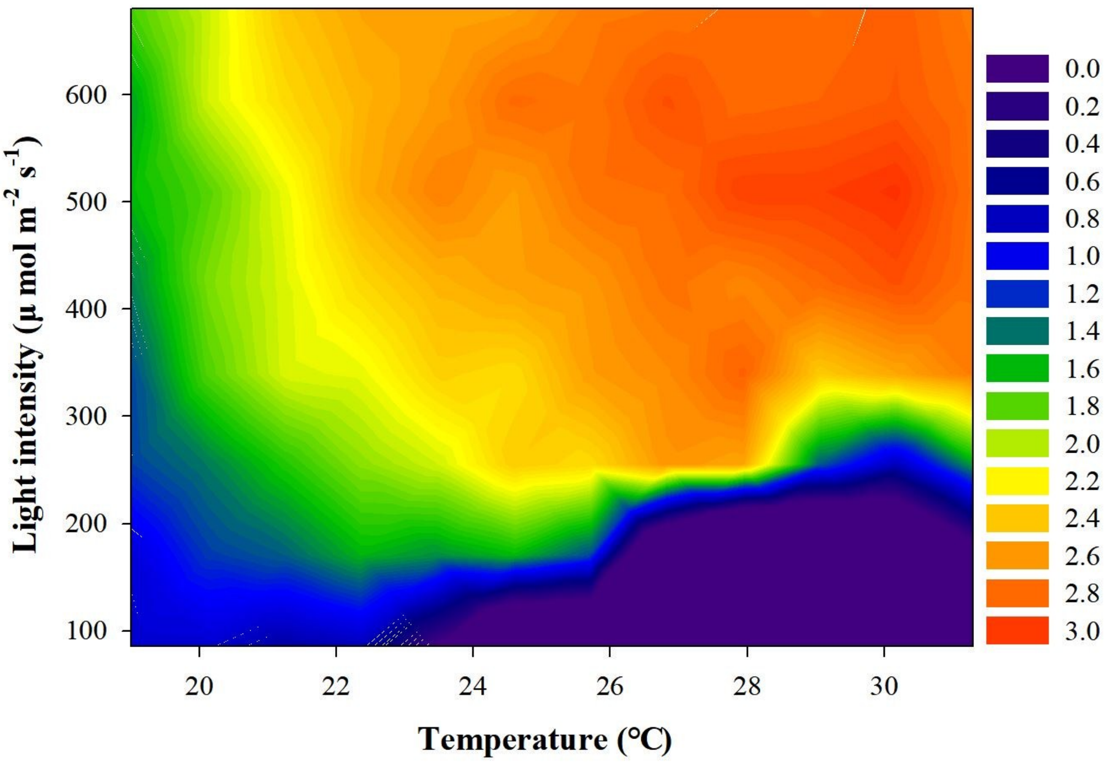
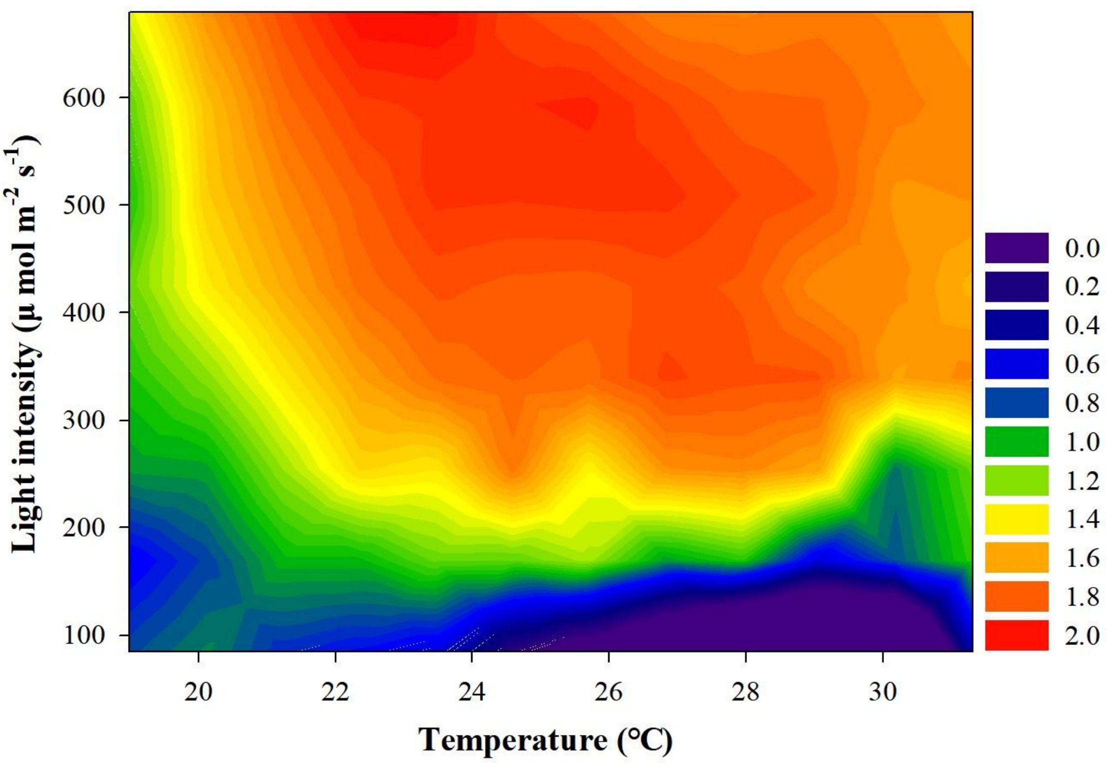

(g)
1st run
2nd run
Specific growth rate (day-1)
Tetraselmis chuii
NaHCO3 concentration (g L-1)
(h)
1st run
2nd run
Specific growth rate (day-1)
Aphanothece sp.
NaHCO3 concentration (g L-1)

Fig. S2. The optimization of temperature and light intensity (1) with 5% (v/v) of CO_2 supply, and (2) with optimal concentrations of $NaHCO_3$: (a) *Micractinium inermum*; (b) *Chlorella sorokiniana*; (c) *Chlorella vulgaris*; (d) *Scenedesmus* sp.; (e) *Nannochloropsis gaditana*; (f) *Tetraselmis suecica*; (g) *Tetraselmis chuii*; and (h) *Aphanothece* sp.. Red color represents high specific growth rate (day^{-1}), and purple for low specific growth rate. Minus specific growth rates were plotted as zero.

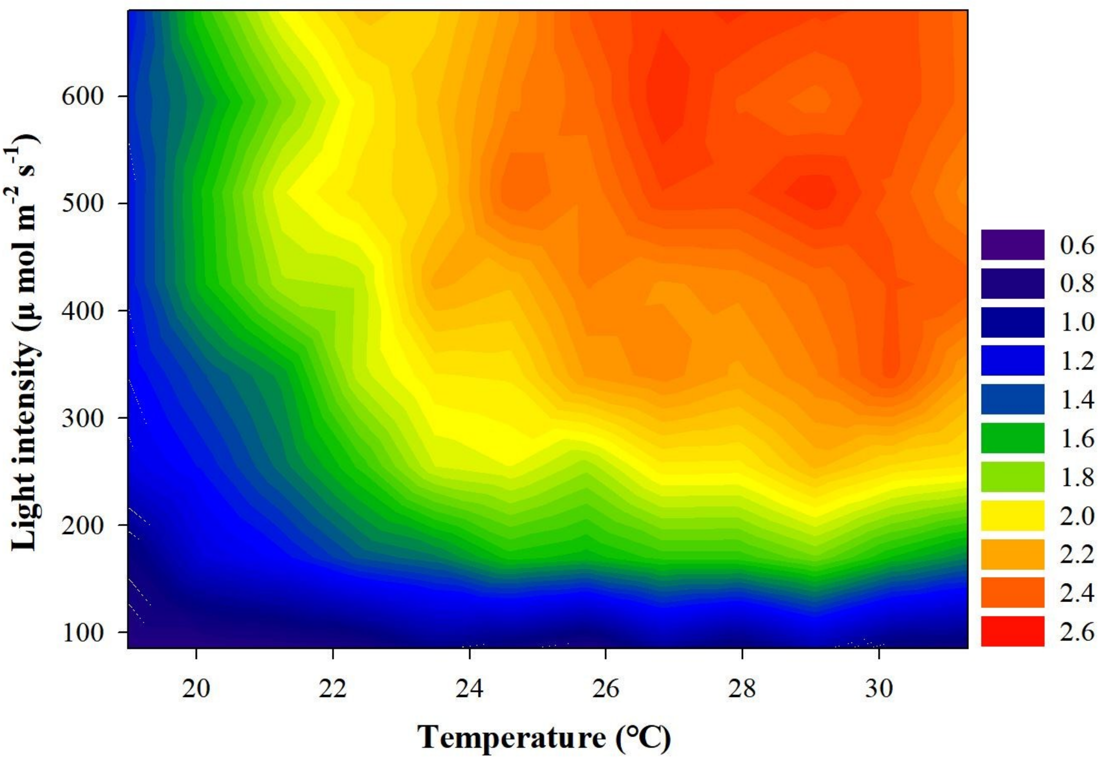
(a1) *Micractinium inermum* with 5% CO_2



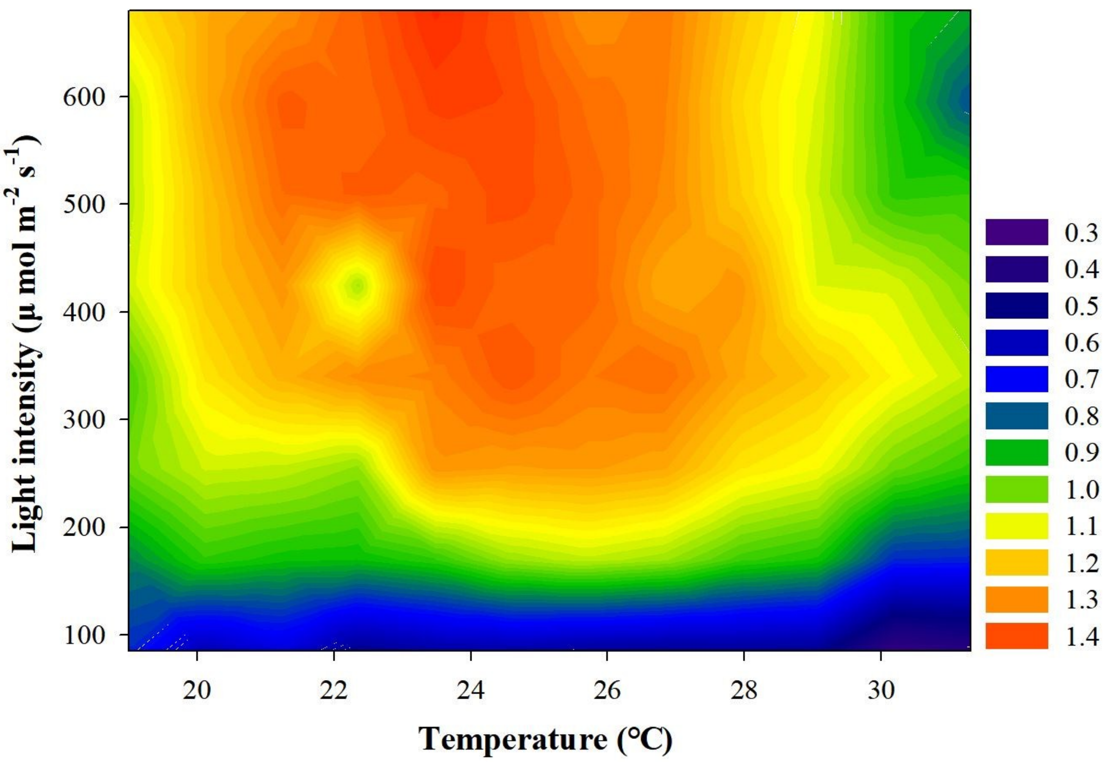
(a2) *Micractinium inermum* with 2.5 g L^{-1} of $NaHCO_3$



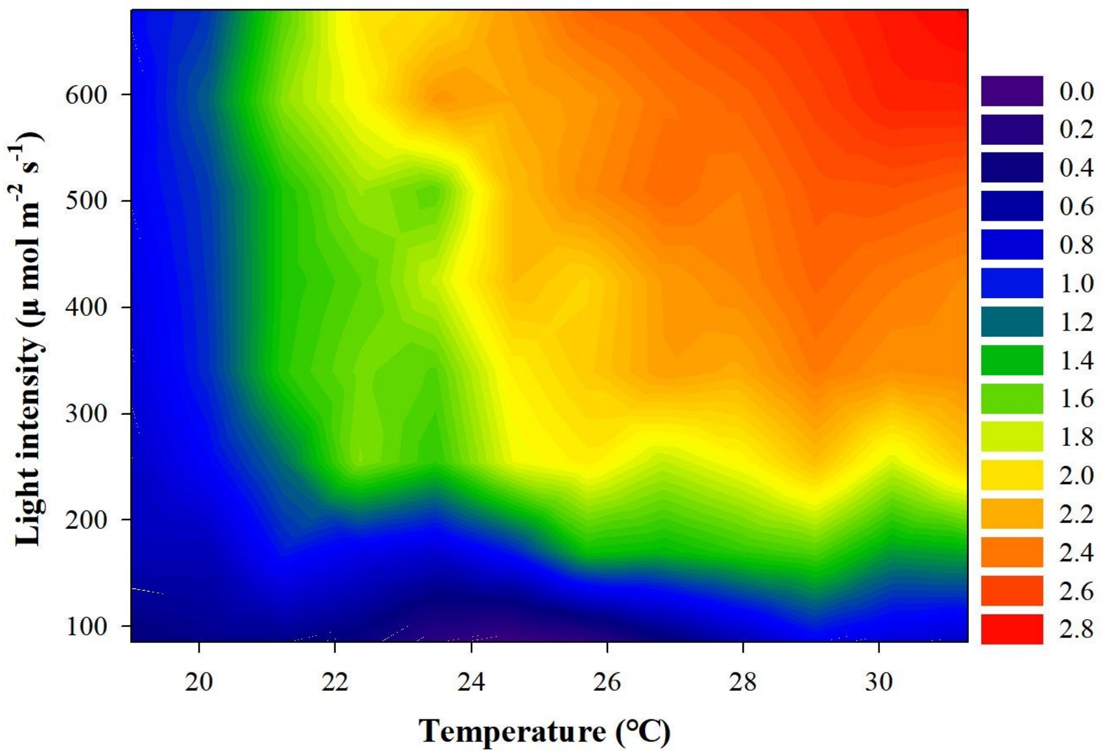
(b1) *Chlorella sorokiniana* with 5% CO_2



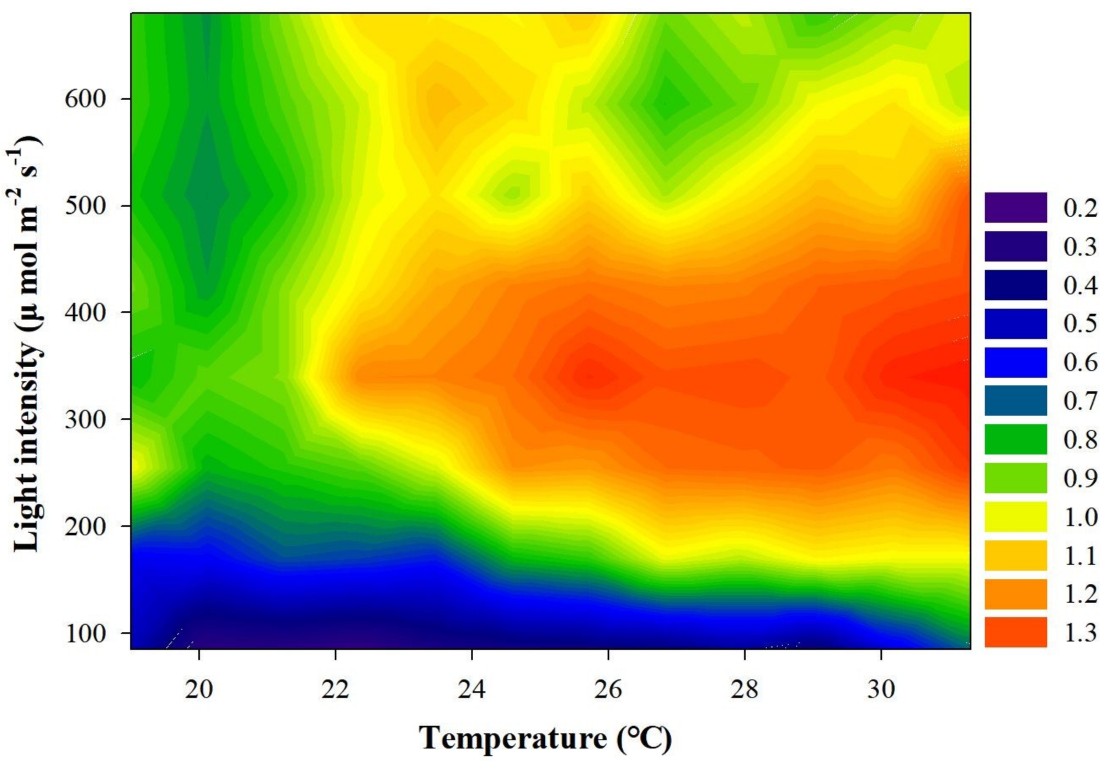
(b2) *Chlorella sorokiniana* with 5 g L^{-1} of $NaHCO_3$



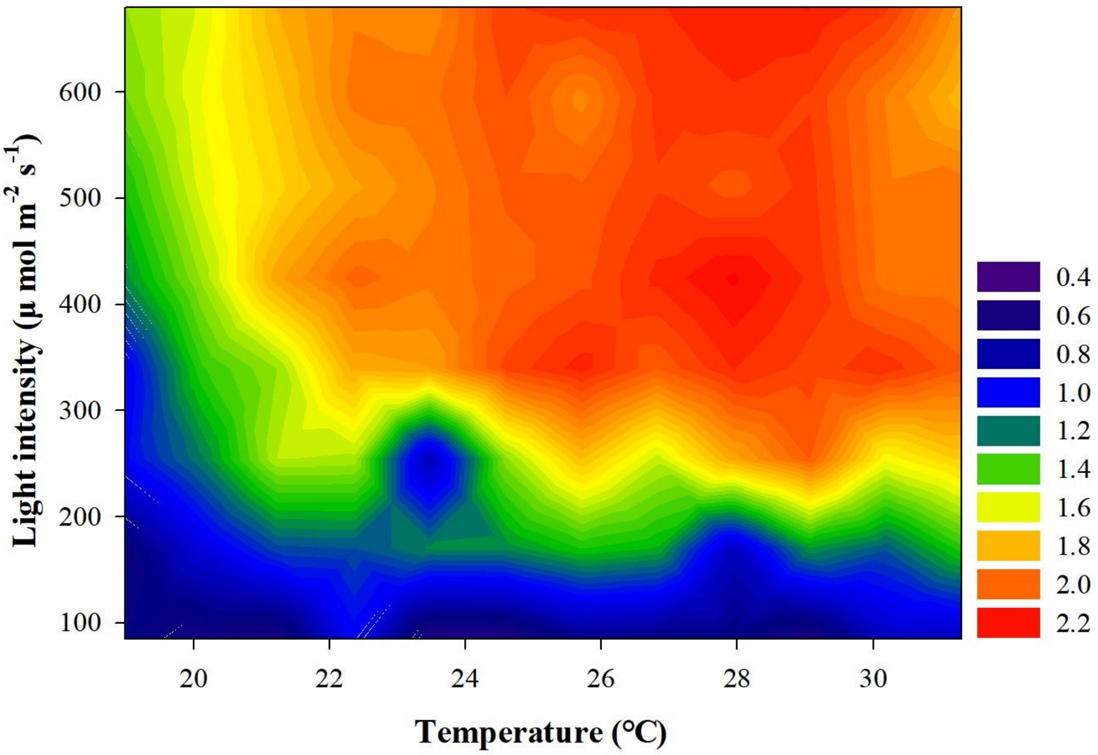
(c1) *Chlorella vulgaris* with 5% CO_2



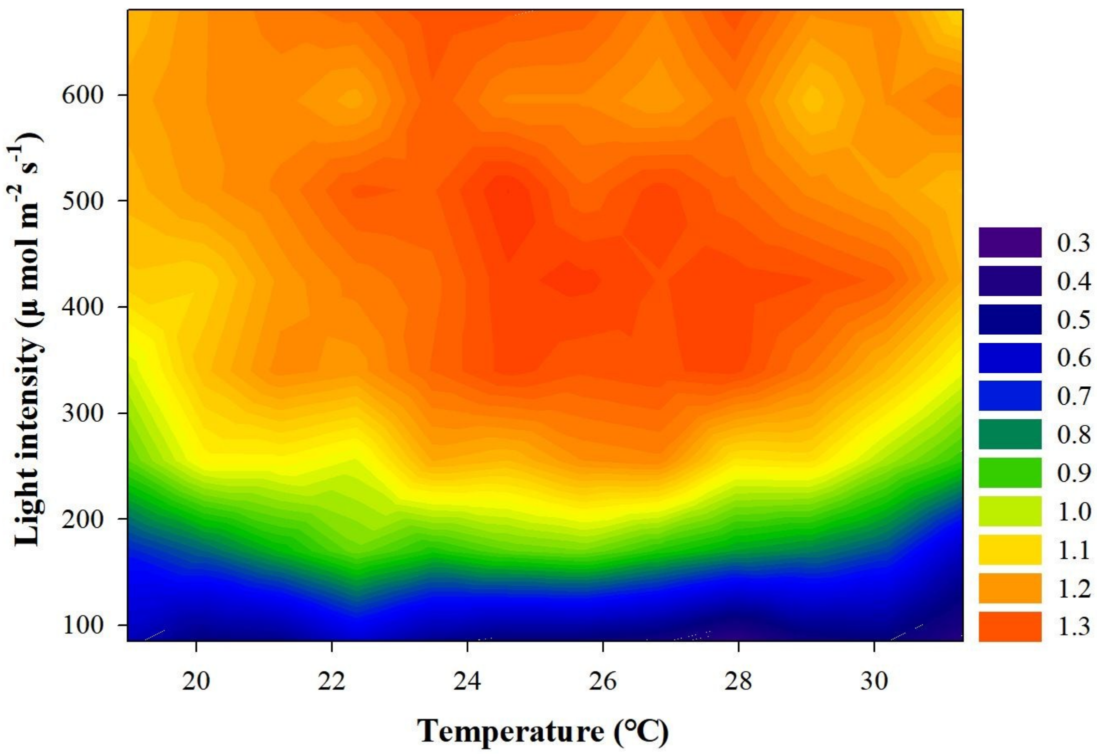
(c2) *Chlorella vulgaris* with 0.5 g L^{-1} of $NaHCO_3$



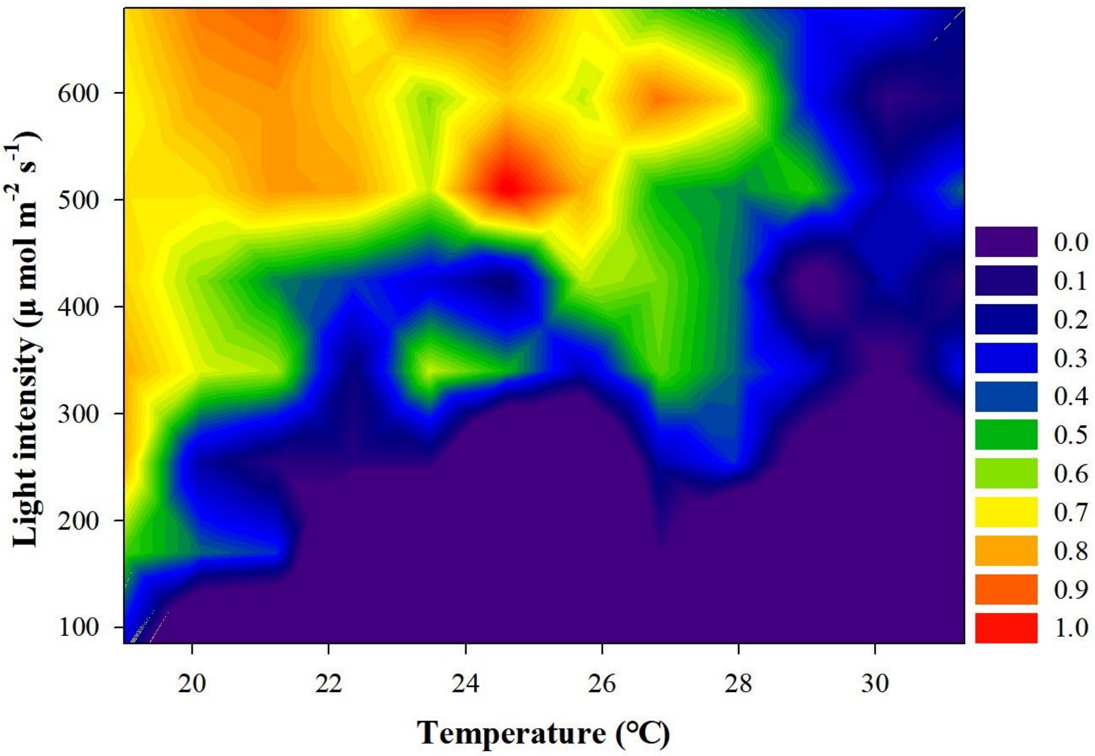
(d1) *Scenedesmus* sp. with with 5% CO_2



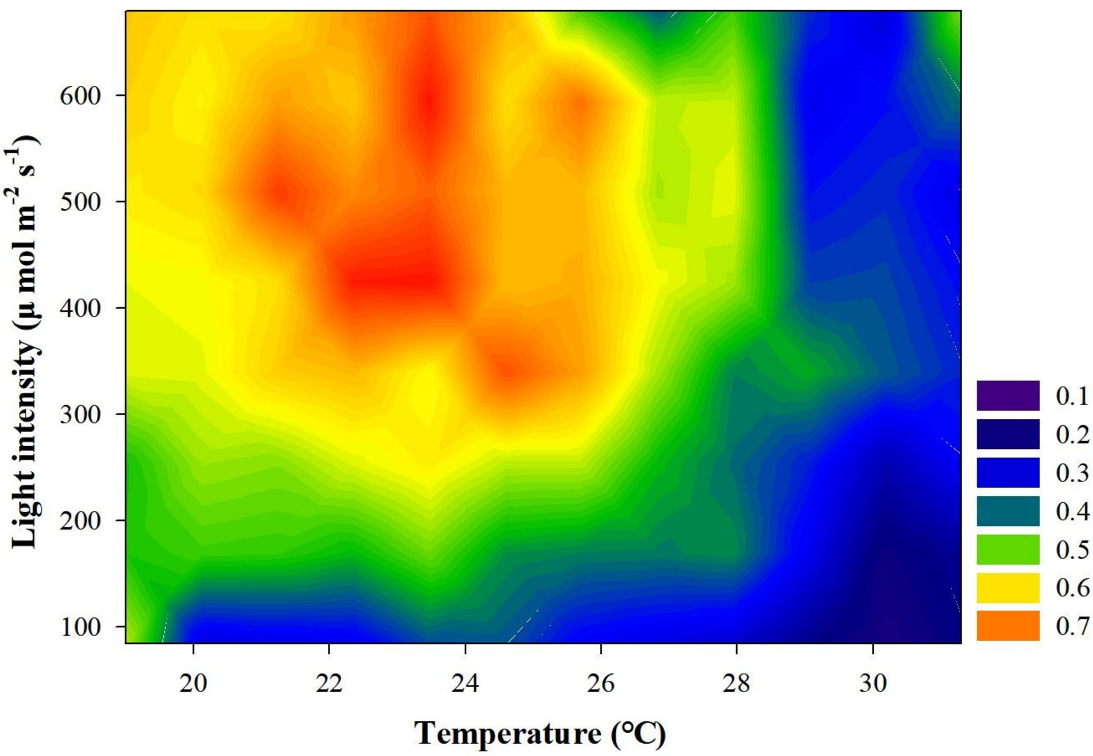
(d2) *Scenedesmus* sp. with 5 g L^{-1} of $NaHCO_3$



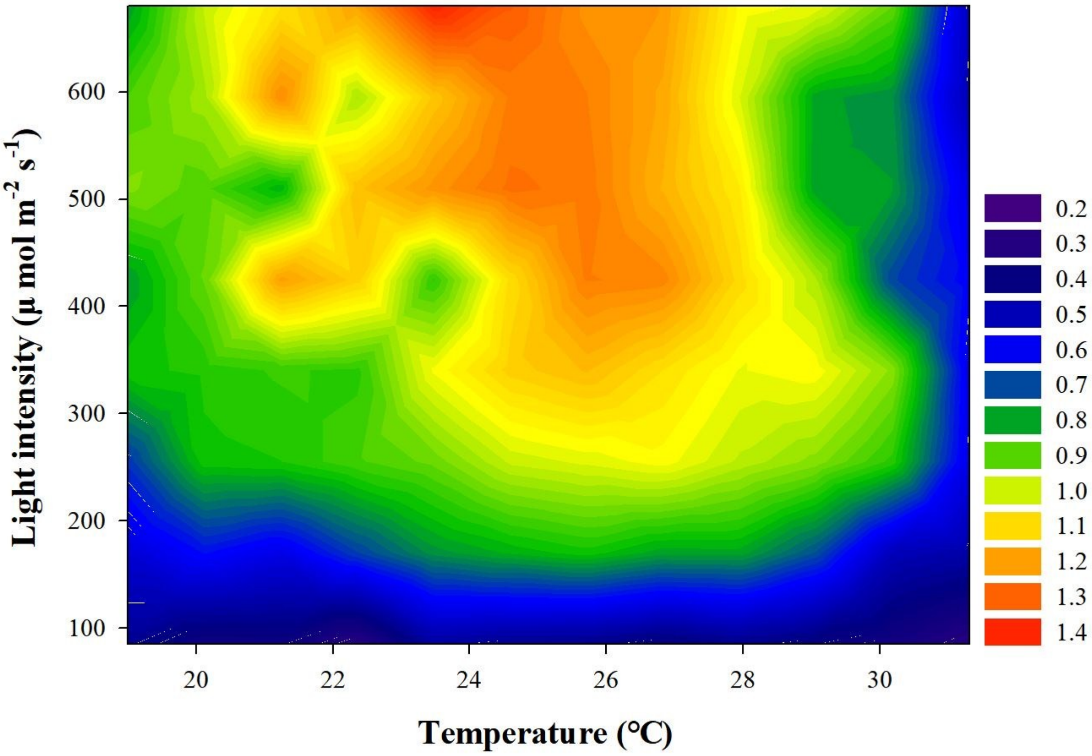
(e1) *Nannochloropsis gaditana* with 5% CO_2



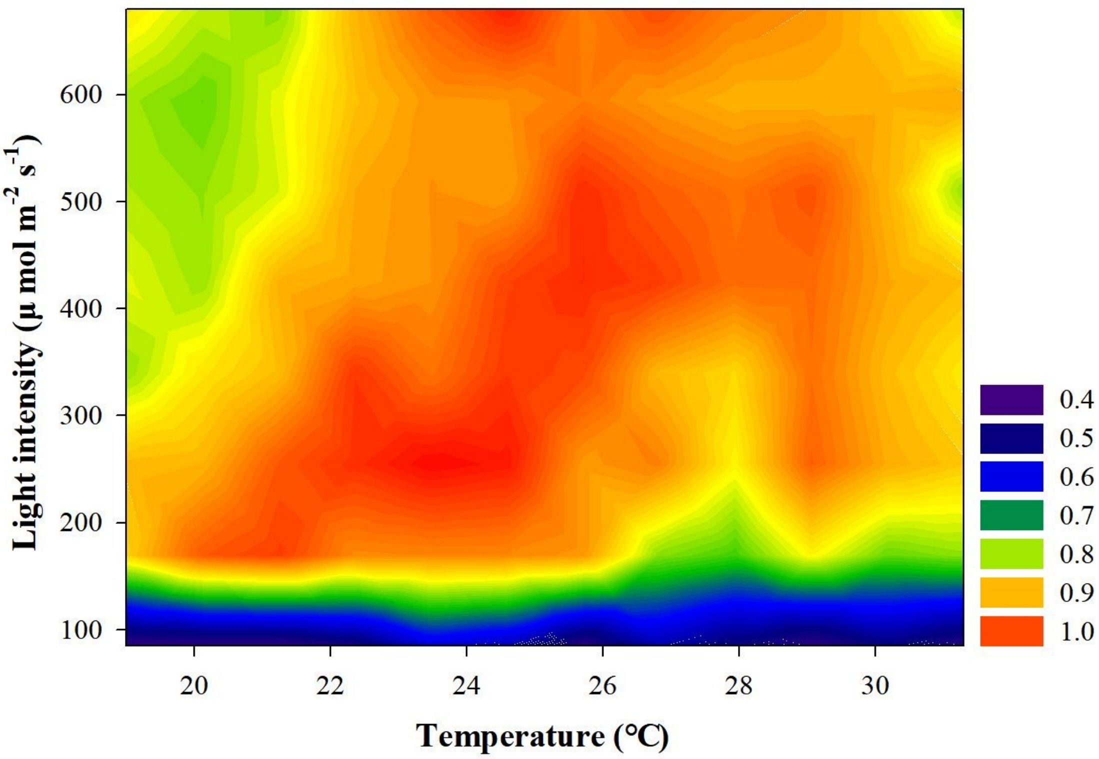
(e2) *Nannochloropsis gaditana* with 1 g L^{-1} of $NaHCO_3$



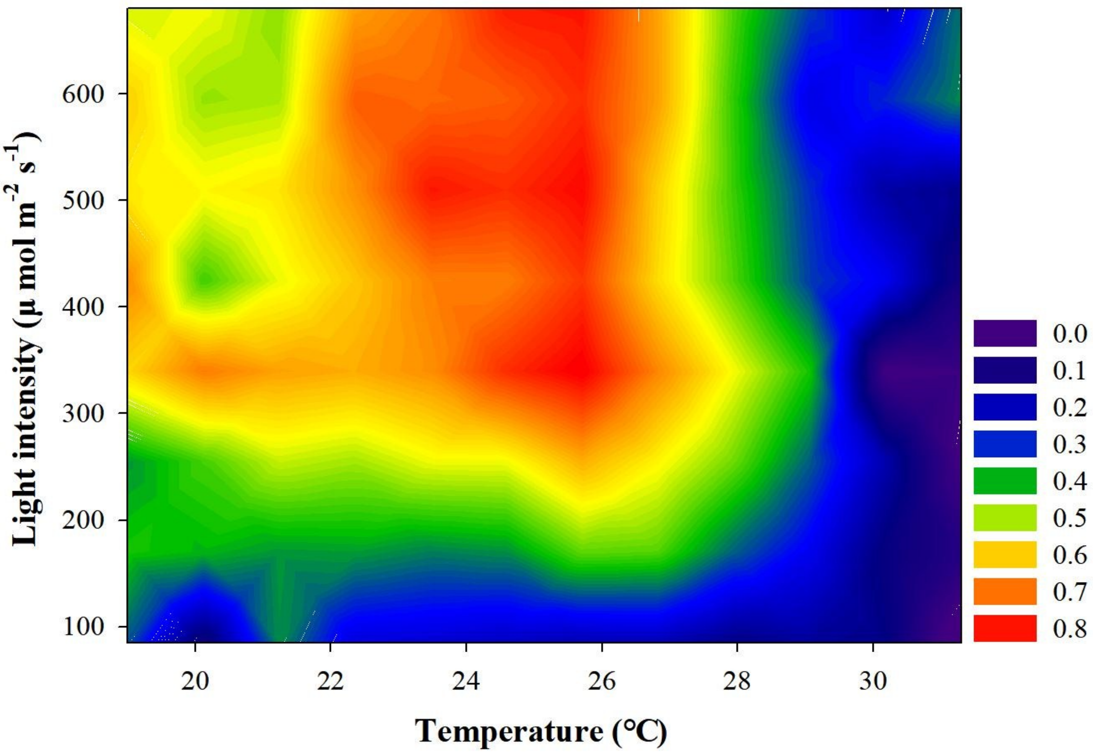
(f1) *Tetraselmis suecica* with 5% CO_2



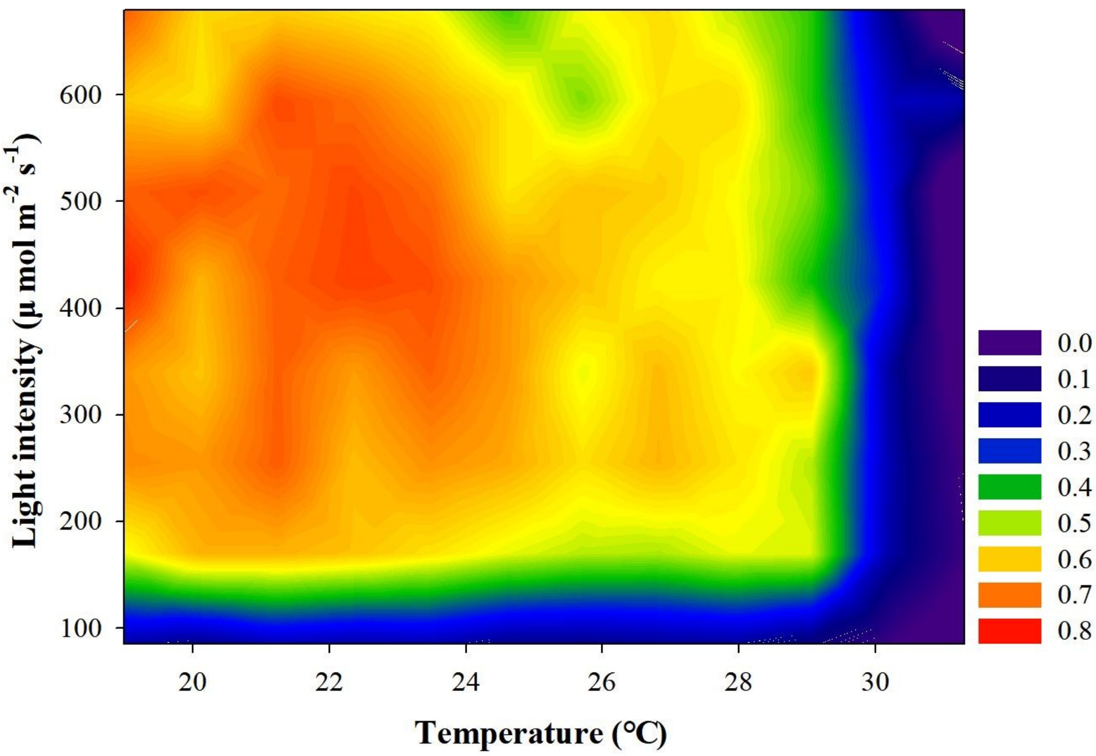
(f2) *Tetraselmis suecica* with 1 g L^{-1} of $NaHCO_3$



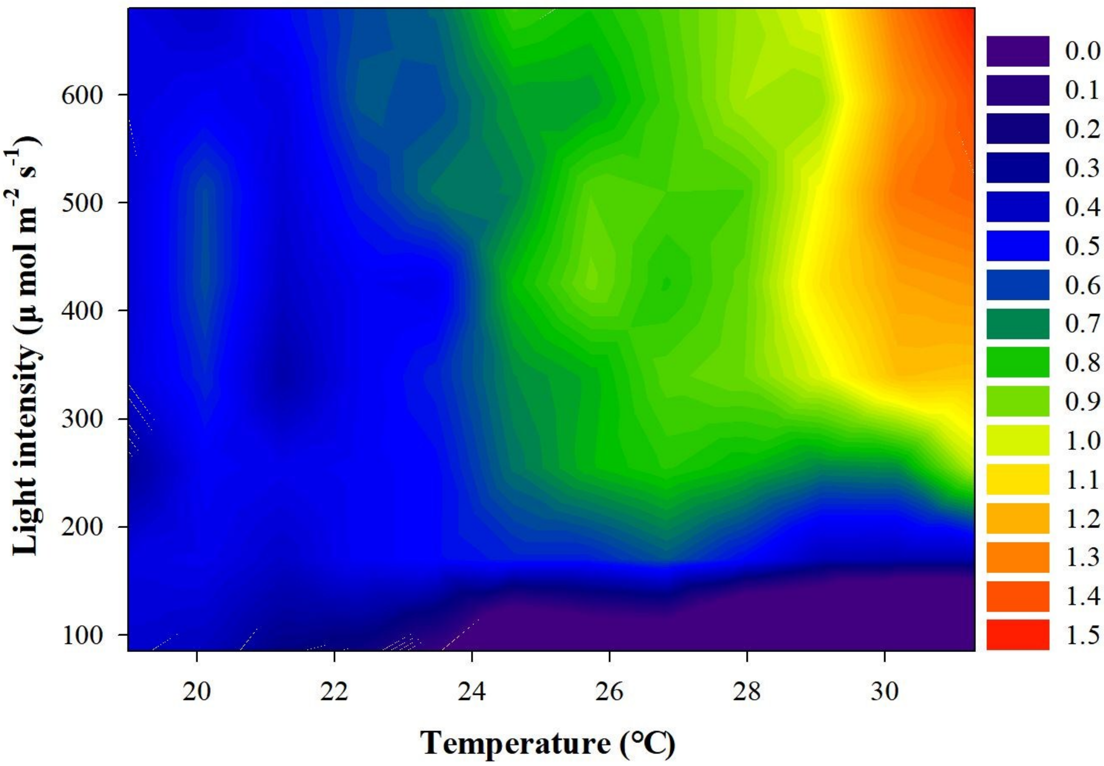
(g1) *Tetraselmis chuii* with 5% CO_2



(g2) *Tetraselmis chuii* with 0.1 g L^{-1} of $NaHCO_3$



(h1) *Aphanothece* sp. with 5% CO_2



(h2) *Aphanothece* sp. with 7.5 g L^{-1} of $NaHCO_3$

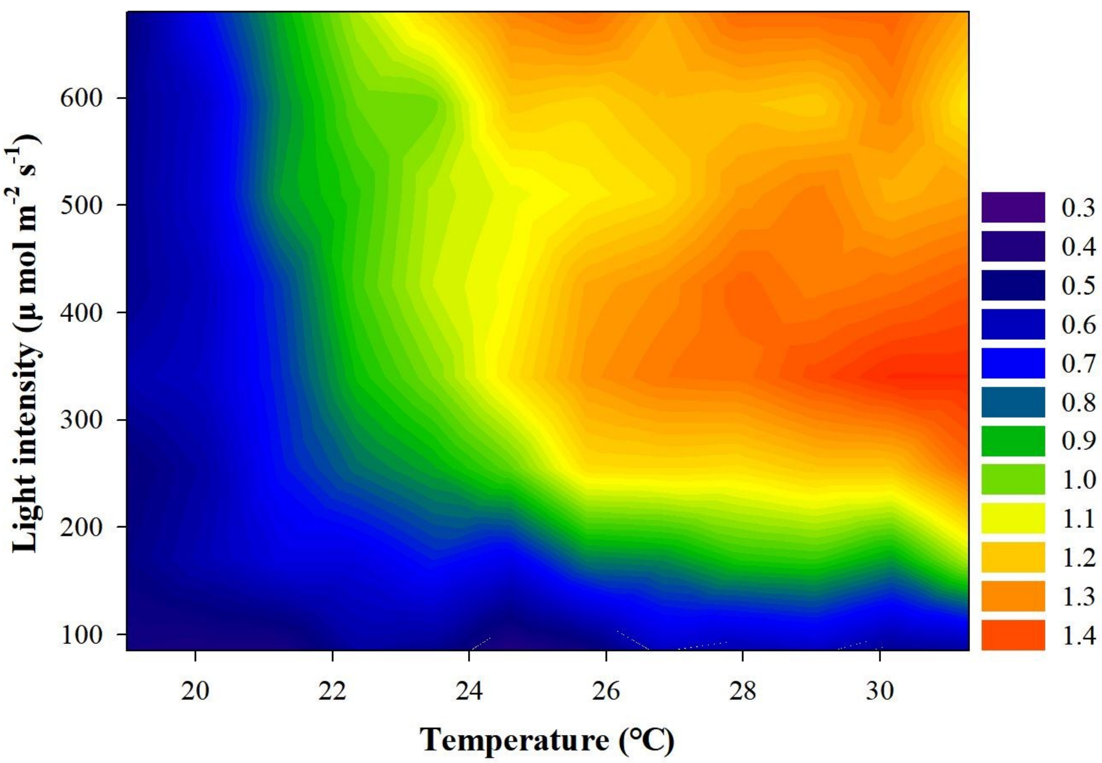


Table S1 Scenario 1: $NaHCO_3$ without transport

Skyonic report based[1]	Power (MW)	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2			
1. Direct carbon capture		−250,000	−250,000
CO_2 emissions			
Emissions from process operations			
2. Electrochemical plant	46.58	173,380	−76,620
3. Outgassed CO_2			
1) 10% of input CO_2 assumed		25,000	1) −51,620
2) 20% of input CO_2 assumed		50,000	2) −26,620
4. HCl used for microalgae cultivation			
1) 10% of input CO_2 assumed		16,088	1) −35,532
2) 20% of input CO_2 assumed		14,319	2) −12,301
Emissions from transportation			
5. Transport of inputs and makeup water		14,055	1) −21,477 2) 1,754
6. Transport of outputs (NaOCl, HCl) and wastewater			
1) 10% of input CO_2 assumed		3,671	1) −17,806
2) 20% of input CO_2 assumed		3,685	2) 5,439
CO_2 reduction from replacing conventional process			
7. Power saved from H_2 production	−21.67	−80,666	1) −98,472 2) −75,227
8. Power saved from Cl_2 production	−18.27	−68,026	1) −166,498 2) −143,253

Table S2 Scenario 2:$NaHCO_3$ with transport (100 km)

Skyonic report based[1]	Power (MW)	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2			
1. Direct carbon capture		−250,000	−250,000
CO_2 emissions			
Emissions from process operations			
2. Electrochemical plant	46.58	173,380	−76,620
3. Outgassed CO_2 1) 10% of input CO_2 assumed 2) 20% of input CO_2 assumed		 25,000 50,000	 1) −51,620 2) −26,620
4. HCl used for microalgae cultivation 1) 10% of input CO_2 assumed 2) 20% of input CO_2 assumed		 16,088 14,319	 1) −35,532 2) −12,301
Emissions from transportation			
5. Transport of inputs and makeup water		14,055	1) −21,477 2) 1,754
6. Transport of outputs (NaOCl, HCl, $NaHCO_3$) and wastewater		4,655	1) −16,822 2) 6,409
CO_2 reduction from replacing conventional process			
7. Power saved from H_2 production	−21.67	−80,666	1) −97,488 2) −74,257
8. Power saved from Cl_2 production	−18.27	−68,026	1) −165,514 2) −142,283

<Scenario 1 and 2>

Scenario 1 and 2 were primarily calculated based on the Skyonic report[1], and then adjusted according to the initial target amounts of CO_2 in functional unit (250,000 ton CO_2/yr).

1. **Direct carbon capture:**

   Target amounts of ton CO_2/yr (250,000 ton CO_2/yr from flue gas emitted by a coal-fired cement kiln).

2. **Electrochemical plant:**

   The amount of energy required for SkyMine® process including flue gas conditioning, carbon capture, electrolysis-based chlor-alkali process, H_2/Cl_2 combustion, product drying/storing/loading and so on. (operating days = 350 days)

	ton/yr
Input	
CO_2	250,000
NaCl	408,417
H_2O	681,153
Energy	**46.58 MW**
Output	
$NaHCO_3$	489,175
HCl	602,434
NaOCl	172,730

Mass balance of SkyMine® process[1]

3. **Outgassed CO_2:**

   Carbon utilization efficiencies of a minimum 80% to a maximum 90% were assumed; therefore, the amount of outgassed CO_2 was calculated from a minimum 10% to a maximum 20% of initial targeted amount of CO_2.

4. **HCl used for microalgae cultivation:**

   0.59 ton HCl required/ton biomass produced[2]

   Among 602,434 ton/yr of HCl produced,

   Case1) 10% of input CO_2 outgassed

   → 74,385 ton/yr of HCl (10.82% of total byproducts)

   Case2) 20% of input CO_2 outgassed

   → 66,196 ton/yr of HCl (9.63% of total byproducts)

   is used for microalgae cultivation to lower the pH of culture medium.

   Therefore,
   Case1) (80,666 + 68,026) * 0.1082 = 16,088 ton CO_2-eq./yr
   Case2) (80,666 + 68,026) * 0.0963 = 14,319 ton CO_2-eq./yr

   among indirect CO_2 reductions, which are obtained from replacing conventional H_2 and Cl_2-production processes, 16,088 and 14,319 ton/yr of CO_2 should be excluded, respectively.

5. **Transport of inputs and makeup water:** 248 + 9,773 + 3,860 + 174 = 14,055

   A. Extraction of salt (NaCl) from sea water through solar evaporation:

      2.2 kWh power consumed/ton NaCl
      408,417 ton NaCl required/yr
      Diesel powered pumps and conveyor belts → 248 ton CO_2-eq./yr

   B. Transport of salt:

      Ship salt by Barge to port: 1,110 km → 9,773 ton CO_2-eq./yr
      Ship by train from port to plant: 588 km, 4,500 tons every 2 weeks → 3,860 ton CO_2-eq./yr

   C. Makeup water:

      681,153 ton water/yr → 174 ton CO_2-eq./yr

6. **Transport of outputs and wastewater:**

Scenario 1 (0 km):

Case1)

489,175 ton $NaHCO_3$ and 74,385 ton HCl is directly used in the algal pond (0 km), and residual (602,434 – 74,385) ton HCl and 172,730 ton NaOCl is transported to the market 100 km away.

NaOCl + residual HCl + wastewater = 2,638 + 905 + 128 = 3,671

Case2)

489,175 ton $NaHCO_3$ and 66,196 ton HCl is directly used in the algal pond (0 km), and residual (602,434 – 66,196) ton HCl and 172,730 ton NaOCl is transported to the market 100 km away.

NaOCl + residual HCl + wastewater = 2,638 + 919 + 128 = 3,685

Scenario 2 (100 km):

Case1)

489,175 ton $NaHCO_3$ and 74,385 ton HCl is transported to the algal pond 100 km away, and residual (602,434 – 74,385) ton HCl and 172,730 ton NaOCl is transported to the market 100 km away.

NaOCl + HCl + $NaHCO_3$ + wastewater = 2,638 + 1,033 + 856 + 128= 4,655

Case2)

489,175 ton $NaHCO_3$ and 66,196 ton HCl is transported to the algal pond 100 km away, and residual (602,434 – 66,196) ton HCl and 172,730 ton NaOCl is transported to the market 100 km away.

NaOCl + HCl + $NaHCO_3$ + wastewater = 2,638 + 1,033 + 856 + 128= 4,655

A. NaOCl:

   172,730 ton NaOCl produced/yr, via heavy duty diesel truck, 20 tons per excursion, 100 km → 2,638 ton CO_2-eq./yr

B. HCl:

Scenario 1:

Case1)

(602,434 – 74,385) ton HCl/yr, via train, 4,500 tons per excursion, 100 km → 905 ton CO_2-eq./yr

Case2)

(602,434 – 66,196) ton HCl/yr, via train, 4,500 tons per excursion, 100 km → 919 ton CO_2-eq./yr

Scenario 2: 602,434 ton HCl produced/yr, via train, 4,500 tons per excursion, 100 km → 1,033 ton CO_2-eq./yr

C. $NaHCO_3$:

489,175 ton $NaHCO_3$ produced/yr, via train, 4,500 tons per excursion, 100 km → 856 ton CO_2-eq./yr

D. Wastewater: 128 ton CO_2-eq./yr

7. Power saved from H_2 production:

Benefits obtained by comparing to common H_2-producing natural gas reformation process (45% Nat. Gas Efficiency (US Average) basis).

8. Power saved from Cl_2 production:

Benefits obtained by comparing to chlor-alkali industry standard.

In the Skyonic report[1], the amount of power saved from Cl_2 production was assumed as 73.28 MW (272,785 ton CO_2-eq./yr). This is the average electricity consumption of a chlorine electrolysis plant producing 1.1 ton of caustic and 0.03 ton of H_2 per ton of Cl_2 (molar ratio of 1.95 : 1.06 : 1).[3]

In this study, for fair calculation, allocation was considered.

73.28 MW *1 / (1.95 + 1.06 + 1) = 18.27 MW

272,785 ton CO_2-eq./yr *1 / (1.95 + 1.06 + 1) = 68,026 ton CO_2-eq./yr

In theory[4],

3.49 ton $NaHCO_3$ required for 1 ton algae biomass

90% carbon utilization efficiency → **3.88 ton $NaHCO_3$/ton biomass**

80% carbon utilization efficiency → **4.36 ton $NaHCO_3$/ton biomass**

		$NaHCO_3$	
	Carbon utilization efficiency (%)	80	90
Net CO_2 emission (ton CO_2-eq./yr)	No transport (0 km)	−143,253	−166,498
	Transport (100 km)	−142,283	−165,514
Biomass produced (ton biomass/yr)		112,196	126,076

Scenario 1 (0 km), 10% CO_2 outgassed:

ton biomass/3.88 ton $NaHCO_3$ → 126,076 ton biomass/489,175 ton $NaHCO_3$

Scenario 1 (0 km), 20% CO_2 outgassed:

ton biomass/4.36 ton $NaHCO_3$ → 112,196 ton biomass/489,175 ton $NaHCO_3$

Scenario 2 (100 km), 10% CO_2 outgassed:

ton biomass/3.88 ton $NaHCO_3$ → 126,076 ton biomass/489,175 ton $NaHCO_3$

Scenario 2 (100 km), 20% CO_2 outgassed:

ton biomass/4.36 ton $NaHCO_3$ → 112,196 ton biomass/489,175 ton $NaHCO_3$

Table S3 Scenario 3: direct flue gas injection without transport

Direct flue gas injection	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2		
1. Direct carbon capture	−250,000	−250,000
CO_2 emissions		
Emissions from process operations		
2. Electricity energy required	2,359	−247,641
3. Outgassed CO_2 1) 75% of input CO_2 assumed 2) 90% of input CO_2 assumed	 187,500 225,000	 1) −60,141 2) −22,641

Table S4 Scenario 4: direct flue gas injection with transport (100 km)

Direct flue gas injection	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2		
1. Direct carbon capture	−250,000	−250,000
CO_2 emissions		
Emissions from process operations		
2. Electricity energy required	2,359	−247,641
3. Outgassed CO_2 1) 75% of input CO_2 assumed 2) 90% of input CO_2 assumed	 187,500 225,000	 1) −60,141 2) −22,641
Emissions from transportation		
4. Compressing CO_2 to 150 atm	84,450	1) 24,309 2) 61,809
5. Transport of CO_2 (100km)	1,750	1) 26,059 2) 63,559

<Scenario 3 and 4>

1. **Direct carbon capture:**

   Target amounts of CO_2 in functional unit (250,000 ton CO_2/yr)

2. **Electricity energy required:**

   22.2 kWh/ton CO_2 of electricity required.[5]

   The source of electricity used in this study was the same as that used in the Skyonic report for the consistency with Scenario 1 and 2 (by a natural gas combined cycle power plant: 2,353 kWh/ton CO_2).

3. **Outgassed CO_2:**

   Carbon utilization efficiencies of a minimum 10% to a maximum 25% were assumed; therefore, the amount of outgassed CO_2 was calculated from a minimum 75% to a maximum 90% of initial targeted amount of CO_2.

4. **Compressing CO_2 to 150 atm:**

   Total mechanical work consumed in compressing CO_2 to 150 atm was assumed as 400.6 MJ/ton CO_2.[6]

   In particular, it was multiplied by 1/0.14, considering that the raw flue gas contains only 14%(v/v) of CO_2.

5. **Transport of CO_2 (100km):**

   The power consumed to transport CO_2 every 100 km was assumed as 8.3 MJ/ton CO_2.[6] It was multiplied by 1/0.14 as well.

Table S5 Scenario 5: MEA-extracted pure CO_2 injection without transport

MEA-extracted pure CO_2 injection	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2		
1. Direct carbon capture	−250,000	−250,000
CO_2 emissions		
Emissions from process operations		
2. Steam energy required	76,213	−173,787
3. Electricity energy required	3,469	−170,318
4. Outgassed CO_2 1) 75% of input CO_2 assumed 2) 90% of input CO_2 assumed	 187,500 225,000	 1) 17,182 2) 54,682

Table S6 Scenario 6:MEA-extracted pure CO_2 injection with transport (100 km)

MEA-extracted pure CO_2 injection	ton CO_2-eq./yr	Cumulative ton CO_2-eq./yr
Input CO_2		
1. Direct carbon capture	−250,000	−250,000
CO_2 emissions		
Emissions from process operations		
2. Steam energy required	76,213	−173,787
3. Electricity energy required	3,469	−170,318
4. Outgassed CO_2 1) 75% of input CO_2 assumed 2) 90% of input CO_2 assumed	 187,500 225,000	 1) 17,182 2) 54,682
Emissions from transportation		
5. Compressing CO_2 to 150 atm	11,823	1) 29,005 2) 66,505
6. Transport of CO_2 (100km)	245	1) 29,250 2) 66,750

<Scenario 5 and 6>

1. **Direct carbon capture:**

   Target amounts of CO_2 in functional unit (250,000 ton CO_2/yr)

2. **Steam energy required:**

   2,010 kg/ton CO_2 of steam is required for MEA extraction, and the energy required to transform water to steam was evaluated as 2.6 MJ/kg steam.[5] Natural gas was assumed to be burned for the steam generation (0.21 kg CO_2/kWh natural gas).[7]

3. **Electricity energy required:**

   32.65 kWh/ton CO_2 of electricity is required.[5]

   The source of electricity used in this study was the same as that used in the Skyonic report for the consistency with Scenario 1 and 2 (by a natural gas combined cycle power plant: 2,353 kWh/ton CO_2).

4. **Outgassed CO_2:**

   Carbon utilization efficiencies of a minimum 10% to a maximum 25% were assumed; therefore, the amount of outgassed CO_2 was calculated from a minimum 75% to a maximum 90% of initial targeted amount of CO_2.

5. **Compressing CO_2 to 150 atm:**

   Total mechanical work consumed in compressing CO_2 to 150 atm was assumed as 400.6 MJ/ton CO_2.[6]

6. **Transport of CO_2 (100km):**

   The power consumed to transport CO_2 every 100 km was assumed as 8.3 MJ/ton CO_2.[6]

In theory[4],

1.83 ton CO_2 required for 1 ton algae biomass

10% carbon utilization efficiency → **18.3 ton CO_2/ton biomass**

25% carbon utilization efficiency → **7.3 ton CO_2/ton biomass**

Scenario 3 (0 km), 75% CO_2 outgassed:

ton biomass/7.3 ton CO_2 → 34,247 ton biomass/250,000 ton CO_2

Scenario 3 (0 km), 90% CO_2 outgassed:

ton biomass/18.3 ton CO_2 → 13,661 ton biomass/250,000 ton CO_2

Scenario 4 (100 km), 75% CO_2 outgassed:

ton biomass/7.3 ton CO_2 → 34,247 ton biomass/250,000 ton CO_2

Scenario 4 (100 km), 90% CO_2 outgassed:

ton biomass/18.3 ton CO_2 → 13,661 ton biomass/250,000 ton CO_2

Scenario 5 (0 km), 75% CO_2 outgassed:

ton biomass/7.3 ton CO_2 → 34,247 ton biomass/250,000 ton CO_2

Scenario 5 (0 km), 90% CO_2 outgassed:

ton biomass/18.3 ton CO_2 → 13,661 ton biomass/250,000 ton CO_2

Scenario 6 (100 km), 75% CO_2 outgassed:

ton biomass/7.3 ton CO_2 → 34,247 ton biomass/250,000 ton CO_2

Scenario 6 (100 km), 90% CO_2 outgassed:

ton biomass/18.3 ton CO_2 → 13,661 ton biomass/250,000 ton CO_2

Table S7 Net CO_2 emissions according to various carbon utilization efficiency

Carbon utilization efficiency (%)	Net CO_2 emissions (ton CO_2-eq./yr)					
	Scenario 1 NaHCO$_3$ 0 km	**Scenario 2** NaHCO$_3$ 100 km	**Scenario 3** Direct flue gas 0 km	**Scenario 4** Direct flue gas 100 km	**Scenario 5** Pure CO_2 0 km	**Scenario 6** Pure CO_2 100 km
10	19,312	20,182	−22,641	63,559	54,682	66,750
20	−3,903	−3,019	−47,641	38,559	29,682	41,750
30	−27,133	−26,234	−72,641	13,559	4,682	16,750
40	−50,363	−49,450	−97,641	−11,441	−20,318	−8,250
50	−73,578	−72,651	−122,641	−36,441	−45,318	−33,250
60	−96,807	−95,866	−147,641	−61,441	−70,318	−58,250
70	−120,037	−119,082	−172,641	−86,441	−95,318	−83,250
80	−143,253	−142,283	−197,641	−111,441	−120,318	−108,250
90	−166,498	−165,514	−222,641	−136,441	−145,318	−133,250

Fig. S3. Net CO_2 emissions according to various carbon utilization efficiency.

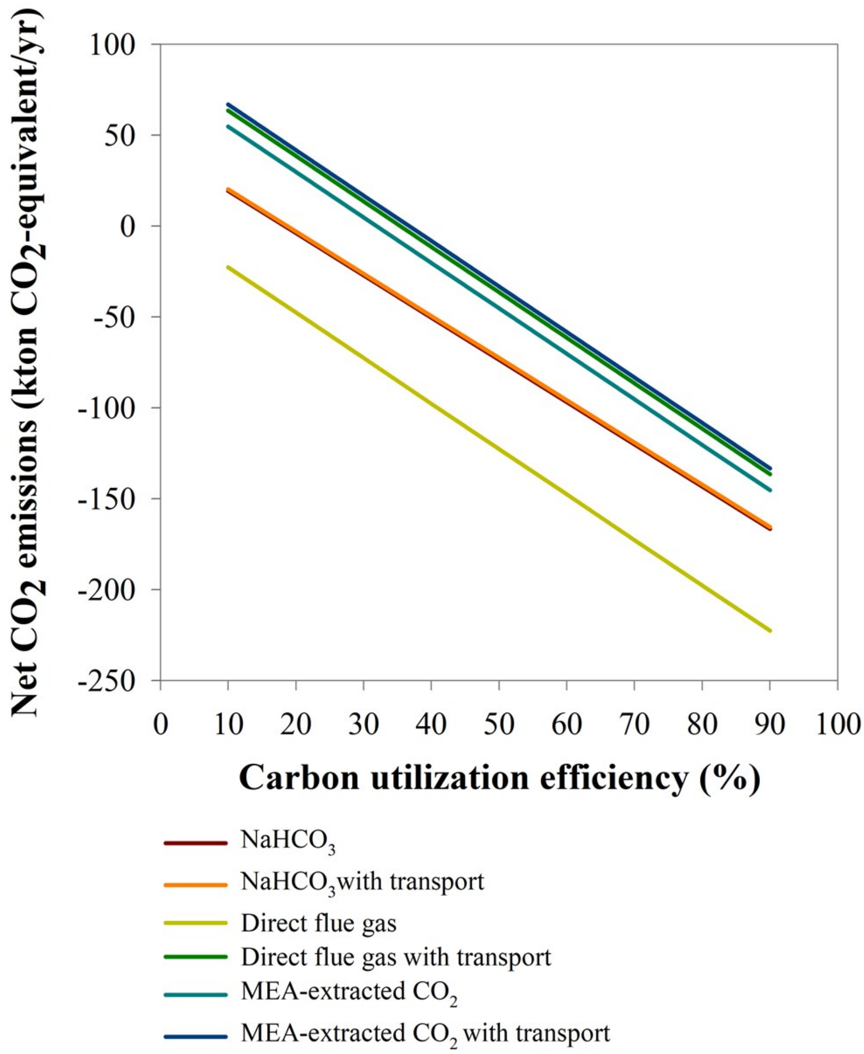
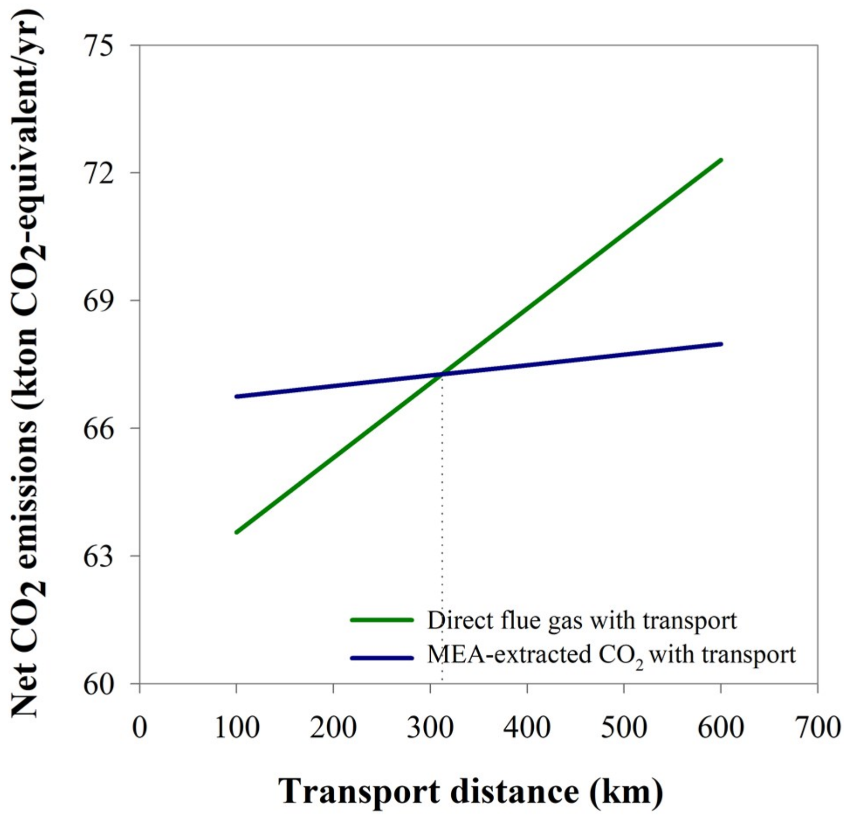


Table S8 Net CO_2 emissions according to the transport distance

	* 10% carbon utilization efficiency assumed Net CO_2 emissions (ton CO_2-eq./yr)	
Transport distance (km)	**Scenario 4** Direct flue gas	**Scenario 6** Pure CO_2
100	63,559	66,750
200	65,309	66,995
300	67,059	67,240
400	68,809	67,485
500	70,559	67,730
600	72,309	67,975

Fig. S4. Net CO_2 emissions according to the transport distance.



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