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Electronic supplementary information (ESI) for

Seasonal Treatment and Economic Performance of an Algal Wastewater System for Energy and Nutrient Recovery

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Table S1 Treatment operating conditions and characteristics of wastewater

		Cold-B	Trans-B	Warm-B	Warm-FB
Operating conditions	Species	Soos	Soos and CCMEE 5587.1	CCMEE 5587.1	CCMEE 5587.1
	Test mode	Batch	Batch	Batch	Fed-batch
	Treatment time (days)	10	10	10[a]	20[b]
	Temperature (°C)[c]	13–37	10–27	31–46	27–42
Input[d]	Source water	Primary clarifier effluent from municipal wastewater treatment plant			
	BOD_5 (mg $O_2 \cdot L^{-1}$)[e]	68.5±7.7	61.5±1.5	111.5±12.0	63.0[f]
	NH_4^+-N (mg $N \cdot L^{-1}$)[g]	24.8±0.3	29.2±0.6	23.7±0.4	22.7±0.2
	PO_4^{3-} (mg$\cdot L^{-1}$)[h]	3.2±0.1	2.1±0.1	3.6±0.04	3.9±0.1
Output[d]	BOD_5 (mg $O_2 \cdot L^{-1}$)	22.5±2.2	17.0±1.4	30.0±1.4	22.5±2.1
	NH_4^+-N (mg $N \cdot L^{-1}$)	19.5±0.4	19.9±2.7	6.4±0.4	9.4±0.3
	PO_4^{3-} (mg$\cdot L^{-1}$)	0.2±0.02	0.2±0.05	0.1±0.01	0.7±0.02
Discharge standards	BOD_5 (mg $O_2 \cdot L^{-1}$)	30			
	NH_4^+-N (mg $N \cdot L^{-1}$)	10			
	PO_4^{3-} (mg$\cdot L^{-1}$)	1			

[a] Although the Warm-B test lasted for 10 days, all discharge standards were met within 4 days.
[b] For the Warm-FB test, 400 L of the treated wastewater (57% of the total volume) was harvested after discharge standards were met, then the reactor was replenished with fresh primary effluent to start a new treatment cycle. The 20-day experiment included 5 continuous cycles, each lasting 2–3 days. All wastewater characteristics (both input and output) for the Warm-FB test were from the last cycle, and HTL experiments in this study also used the biomass harvested from the last cycle.
[c] Temperatures here refer to the culture temperature in algal photobioreactors.
[d] Input denotes the input into algal treatment system (primary clarifier effluent from wastewater treatment plant), and output denotes the algal-treated wastewater.
[e] Dissolved BOD_5 was measured instead of total BOD_5 following the protocol in [1], as the algal biomass would affect total BOD_5. Results were shown as average±max/min of duplicate analysis.
[f] No error values because duplicate analysis yielded the same results.
[g] NH_4^+-N was measured using Hach Salicylate kit,[1] results were shown as average values±standard deviations of triplicate analysis.
[h] PO_4^{3-} was measured using Hach PhosVer 3 kit,[1] results were shown as average values±standard deviations of triplicate analysis.

Table S2 Elemental compositions of algal biomass[a]

	Cold-B	Trans-B	Warm-B	Warm-FB
C (dw%)	31.4±0.1	46.9±0.01	40.0±0.03	40.1±0.04
H (dw%)	5.3±0.02	7.1±0.1	6.1±0.02	6.2[b]
N (dw%)	4.9±0.04	9.0[b]	7.3±0.02	8.2[b]
P (dw%)	1.1±0.01	1.7±0.1	0.8±0.1	0.9±0.03
Volatile O (dw%)[c]	28.2±0.4	25.1±0.1	28.5±0.2	27.5±0.1
HHV (MJ$\cdot kg^{-1}$)[d]	13.1±0.1	21.4±0.1	17.2±0.05	17.5±0.03

[a] Results are shown as average±max/min of duplicate analysis; errors for volatile oxygen contents and higher heating values (HHV) were calculated by error propagation methods.
[b] No error value because duplicate analysis yielded the same results.
[c] Calculated by difference as 1 - C - H - N - P - ash (all on dry weight basis, dw%).
[d] Calculated using Dulong's equation.[2]

Table S3 Characteristics of HTL biocrude and biochar products[a]

		Cold-B	Trans-B	Warm-B	Warm-FB
300°C (Biocrude)	C (%)	70.4±0.3	70.2±0.4	70.3±0.6	71.0±0.7
	H (%)	8.4±0.1	8.8±0.02	8.4±0.2	8.4±0.2
	N (%)	6.9±0.002	6.9±0.1	6.4±0.01	7.0±0.1
	O (%)[b]	14.4±0.3	14.1±0.3	14.8±0.6	13.6±0.8
	HHV ($MJ\cdot kg^{-1}$)[c]	33.1±0.1	33.8±0.1	33.1±0.3	33.6±0.4
350°C (Biocrude)	C (%)	73.5±0.2	71.2±0.9	73.0±0.4	72.5±0.1
	H (%)	8.5±0.04	8.6±0.1	8.8±0.04	8.8±0.03
	N (%)	6.4±0.2	6.5±0.2	6.1±0.1	6.5±0.1
	O (%)[b]	11.6±0.2	13.7±0.9	12.2±0.4	12.2±0.1
	HHV ($MJ\cdot kg^{-1}$)[c]	34.9±0.1	33.8±0.3	35.0±0.2	34.9±0.1
300°C (Biochar)	C (%)	26.6±0.2	[d]	24.7±2.1	25.4±3.8
	H (%)	3.8±0.01	[d]	3.6±0.3	3.9±0.4
	N (%)	2.9±0.1	[d]	2.8±0.2	3.1±0.5
	P (%)	2.5±0.2	[d]	3.2±0.05	3.4±0.1
350°C (Biochar)	C (%)	23.6±3.7	11.6[e]	15.1[e]	21.9[e]
	H (%)	3.1±0.3	1.4[e]	2.6[e]	3.3[e]
	N (%)	2.4±0.3	2.8[e]	2.2[e]	3.3[e]
	P (%)	2.9±0.1	[d]	[d]	[d]

[a] Results are shown as average±max/min of duplicate analysis; errors for oxygen contents and HHV were calculated by error propagation methods; all elemental contents were shown as weight percentage (wt%).
[b] Calculated by difference as 1 - C - H - N.
[c] Calculated using Dulong's equation.[2]
[d] Data unavailable due to the scarcity of sample.
[e] No duplicate analysis due to the scarcity of sample.

Table S4 Characteristics of HTL aqueous products[a]

		Cold-B	Trans-B	Warm-B	Warm-FB
300°C	TOC ($mg\ C\cdot L^{-1}$)	11800±1500	29500±200	28000±500	31300±4300
	TN ($mg\ N\cdot L^{-1}$)	4000±300	11400±700	8600±200	10600±800
	NH_4^+-N ($mg\ N\cdot L^{-1}$)	1980±170	4870±70	3910±220	3670±50
	NH_4^+-N/TN (%)	50.0±6.0	42.6±2.8	45.6±2.9	34.7±2.7
	PO_4^{3-} ($mg\cdot L^{-1}$)	42±16	732±21	137±10	6±3
350°C	TOC ($mg\ C\cdot L^{-1}$)	16100±1000	26600±2800	23800±2200	19900±1000
	TN ($mg\ N\cdot L^{-1}$)	5300±100	12600±500	9800±700	10300±600
	NH_4^+-N ($mg\ N\cdot L^{-1}$)	3350±30	8450±900	5050±20	6050±260
	NH_4^+-N/TN (%)	63.6±1.1	67.3±7.5	51.6±3.5	59.0±4.0
	PO_4^{3-} ($mg\cdot L^{-1}$)	115±7	414±111	107±1	93±7

[a] Results are shown as average±max/min of duplicate analysis; errors for NH_4^+-N/TN ratios were calculated by error propagation methods; NO_2^-/NO_3^- contents were below detection limits for all batches.

Table S5 Summary of annual product yields and economic analysis (Scenarios 1–3)[a]

		Cold-B	Trans-B	Warm-B	Average
	Biofuel[b]				
Cost (MM $\$\cdot yr^{-1}$)[c]	Capital	0.40	0.40	0.40	0.40
	Operating	0.65	0.66	0.66	0.66
	Financial	0.98	1.01	1.00	1.00
Revenue	Biofuel yields (MM GGE$\cdot yr^{-1}$)[d]	0.28	0.70	0.55	0.51
	Biofuel sales (MM $\$\cdot yr^{-1}$)[e]	0.78	1.95	1.55	1.43
Net revenue (MM $\$\cdot yr^{-1}$)		-1.26	-0.12	-0.51	-0.63
	Nutrient Products				
Yields (MM kg$\cdot yr^{-1}$)	$(NH_4)_2SO_4$[f]	0.60	1.77	1.12	1.16
	Struvite[g]	0.60	0.96	0.45	0.67
Revenue (MM $\$\cdot yr^{-1}$)[h]	$(NH_4)_2SO_4$	0.35	1.04	0.66	0.68
	Struvite	0.25	0.41	0.19	0.28
	Sum	0.60	1.45	0.85	0.97

[a] Costs, revenues, and net revenues are shown in million 2014 U.S. dollars per year (MM $\$\cdot yr^{-1}$) assuming a feedstock flow rate of 576 U.S. ton per day (on dry ash-free basis). Results for Cold-B, Trans-B, and Warm-B were calculated using the respective experiment data (350°C HTL conversion) as inputs of the model described in a previous study;[3] the average results were calculated using the average HTL results of Cold-B, Trans-B, and Warm-B. Warm-FB gave similar results as Warm-B thus not presented.

[b] Liquid hydrocarbon fuels in gasoline and diesel ranges.[3]

[c] Refer to Table S6 for cost breakdown.

[d] Gasoline gallon equivalent per year.

[e] Based on a price of \$2.79 GGE^{-1} as commercial gasoline (average price for 2010–2019 reported by U.S. Energy Information Administration).[4]

[f] Yields calculated assuming 92.3% of NH_4^+-N in HTL aqueous products was converted to $(NH_4)_2SO_4$ based on a previous study.[5]

[g] Magnesium ammonium phosphate (MAP) with a molecular formula of $MgNH_4PO_4\cdot 6H_2O$, yield calculated assuming 92.2% of P in the algal feedstock was converted to struvite based on a previous study.[5]

[h] Based on unit prices of \$0.588 kg^{-1} for $(NH_4)_2SO_4$ and \$0.423 kg^{-1} for struvite.[5]

Table S6 Cost breakdown (Scenarios 1–3)[a]

			Cold-B	Trans-B	Warm-B	Average
Capital						
Capital (lifetime, MM $\$$)	Inside battery limits[b]	HTL	2.36	2.38	2.38	2.38
		Biocrude hydrotreating	0.83	0.84	0.83	0.83
		Heavy oil hydrocracking	0.21	0.21	0.21	0.21
		Catalytic hydrothermal gasification	2.19	2.21	2.20	2.20
	Outside battery limits[c]		0.94	0.95	0.95	0.95
	Total non-installed direct cost[d]		0.98	0.99	0.98	0.98
	Total indirect cost[e]		4.50	4.55	4.53	4.53
	Working capital[f]		0.60	0.61	0.60	0.60
	Sum		12.61	12.74	12.68	12.68
Capital (annualized, MM $\$\cdot\mathrm{yr}^{-1}$)[g]			0.40	0.40	0.40	0.40
Operating (MM $\$\cdot\mathrm{yr}^{-1}$)						
Variable operating cost	Catalysts[h]		0.15	0.16	0.15	0.15
	Utilities[i]		0.14	0.15	0.15	0.15
Fixed operating cost[j]			0.35	0.36	0.36	0.36
Sum			0.65	0.66	0.66	0.66
Financial (MM $\$\cdot\mathrm{yr}^{-1}$)						
Income tax[k]			0.27	0.29	0.28	0.28
Loan payment[l]			0.72	0.72	0.72	0.72
Sum			0.98	1.01	1.00	1.00

[a] All costs are shown in million 2014 U.S. dollars and calculated using a techno-economic analysis model detailed in Leow et al.[3] The plant was assumed to have a building time of 3 years (before operation started) and an operating time of 30 years. The startup time was 0.5 years, during which the revenue was 50% of regular revenue, and variable operating cost was 75% of the regular operating cost; internal rate of return was 10%.

[b] Capital costs for inside and outside batter limits were scaled from the original equipment cost[3,6] based on material flow rates following method described in Leow et al.[3]

[c] Including hydrogen plant, power generation, steam system, and cooling water system.

[d] Including warehouse building, site development, and additional piping, which were calculated as 17.5% of inside battery limits.

[e] Including prorated expenses calculated as 60% of the total direct cost (sum of inside battery limits, outside battery limits, and total non-installed costs).

[f] Calculated as 5% of fixed capital investment (sum of total direct cost and total indirect cost).

[g] Capital costs averaged to each operating year (working capital not included as it would be paid back at the end of operation).

[h] Including catalysts for catalytic hydrothermal gasification, hydrotreating, hydrocracking, and hydrogen plant.

[i] Including natural gas, electricity, and makeup water.

[j] Including staff salary, labor burden, maintenance, insurances, and taxes.

[k] Loan principle was 60% of fixed capital investment (40% equity), loan interest was 8% and loan term was 10 years.

[l] Income tax was 35% of profit.

Table S7 Annual cost and revenue breakdown (Scenarios 4–6)[a]

		Cold-B	Trans-B	Warm-B	Average-B
		Scenario 4			
Cost	Capital	0.40	0.40	0.40	0.40
	Operating	0.65	0.66	0.66	0.66
	Financial	0.99	1.01	1.01	1.01
	Sum	2.04	2.08	2.07	2.06
Revenue	Hydrocarbon fuel	0.75	1.98	1.49	1.33
	Ethanol	0	0	0	0
	$(NH_4)_2SO_4$[b]	0.27	0.86	0.56	0.56
	Struvite	0.25	0.41	0.19	0.28
	Sum	1.28	3.25	2.24	2.17
Net revenue		-0.77	1.17	0.17	0.11
		Scenario 5			
Cost	Capital	0.49	0.49	0.49	0.49
	Operating	1.12	1.13	1.13	1.13
	Financial	1.46	1.46	1.46	1.46
	Sum	3.07	3.09	3.09	3.08
Revenue	Hydrocarbon fuel	1.04	2.00	1.93	1.64
	Ethanol	1.54	0.84	0.59	0.99
	$(NH_4)_2SO_4$	0.35	1.04	0.66	0.68
	Struvite	0.25	0.41	0.19	0.28
	Sum	3.18	4.29	3.38	3.60
Net revenue		0.10	1.19	0.29	0.52
		Scenario 6			
Cost	Capital	0.49	0.49	0.49	0.49
	Operating	1.12	1.13	1.13	1.13
	Financial	1.46	1.47	1.47	1.47
	Sum	3.07	3.09	3.09	3.08
Revenue	Hydrocarbon fuel	0.94	2.07	2.07	1.67
	Ethanol	1.88	1.07	0.79	1.26
	$(NH_4)_2SO_4$[b]	0.27	0.86	0.56	0.56
	Struvite	0.25	0.41	0.19	0.28
	Sum	3.35	4.41	3.62	3.78
Net revenue		0.28	1.32	0.53	0.69

[a] Costs for Scenario 4 were calculated in the same manner as Scenarios 1–3 with biochemical compositions of peak-storage algae; costs and revenues for Scenarios 5 and 6 were calculated based on Li et al.[7] assuming the same wastewater algae loading (25.6 dry U.S. ton per day, TPD) and total plant scale (576 TPD), but Scenario 5 was for baseline algae while Scenario 6 for peak-storage algae; all costs and revenues are shown in million 2014 U.S. dollars per year (MM $\$\cdot yr^{-1}$).

[b] Yields of ammonium sulfate were proportionally adjusted based on the protein contents of baseline and peak-storage algae.

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