Design of Raceway Ponds for Algae Biomass Production using Produced Water

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Presentation outline

1. Algae based-Biodiesel
2. Algae oil Production
3. Research Objective
4. Mathematical Modeling
5. Results
6. Future directions
7. Questions?

Motivation – Produced water

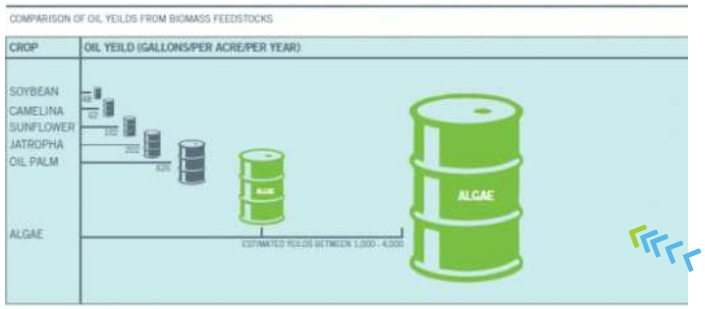
- Salty water trapped in the reservoir rock and brought up along with oil or gas during production

- These waters exist under high pressures and temperatures
- It can contain very minor amounts of chemicals, oil, and metals
- Every year in the United States about 800 billion gallons of produced water is brought to the surface along with oil and gas and about 98% of this water is routinely disposed as a waste product
- However, these large quantities of saline water have great potential value for algal biofuel production
- Scientists recently were successful in conducting the first pilot-scale test of algae growth using water from an oil-production well in Jal, New Mexico

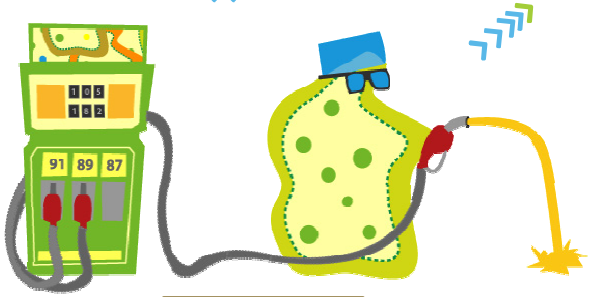
Advantages

Higher growth rates & productivities

CO_2 capture



Higher oil yield



Algae oil

Grown on non-arable land and using produced water

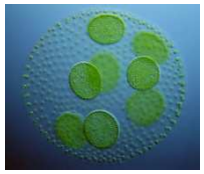
Food vs. fuel

No sulfur, non-toxic & biodegradable

Challenges

High capital, operating & production costs

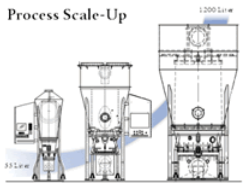
Relatively new technology



Variety of algae strains

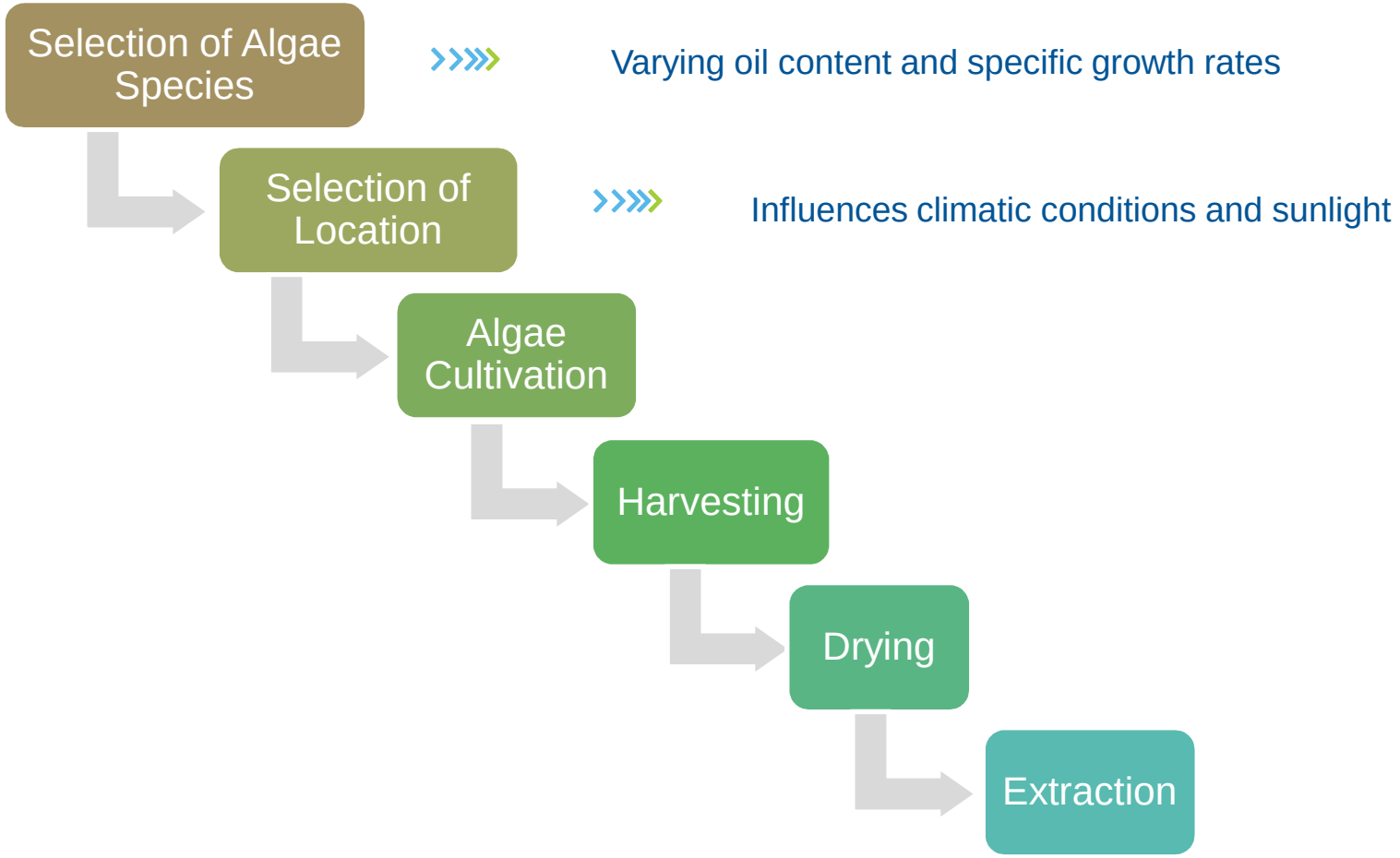
Algae biofuel

Lack of optimal design of cultivation systems



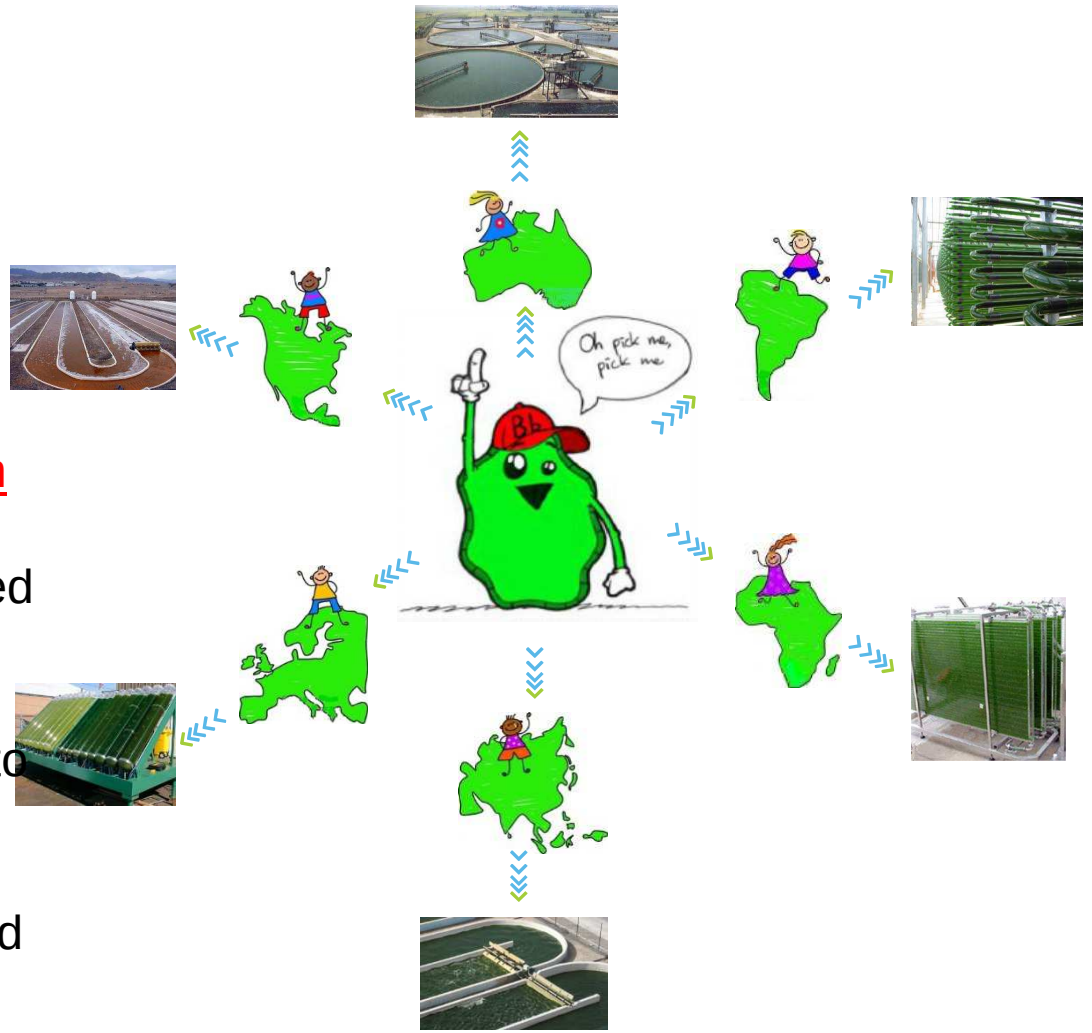
Difficulty in scaling up

Algae oil Production



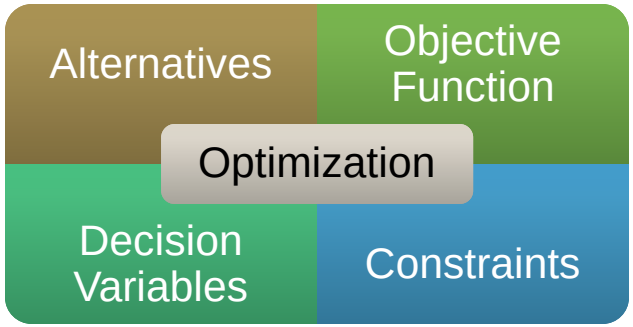
Research Objective

- Find a suitable algae species for cultivation
- Find the most suitable location to cultivate the selected algae strain
- Design an optimal cultivation system depending on the species and location selected
- The purpose of the study is to design a cultivation system that suits an algae species when cultivated at a selected location



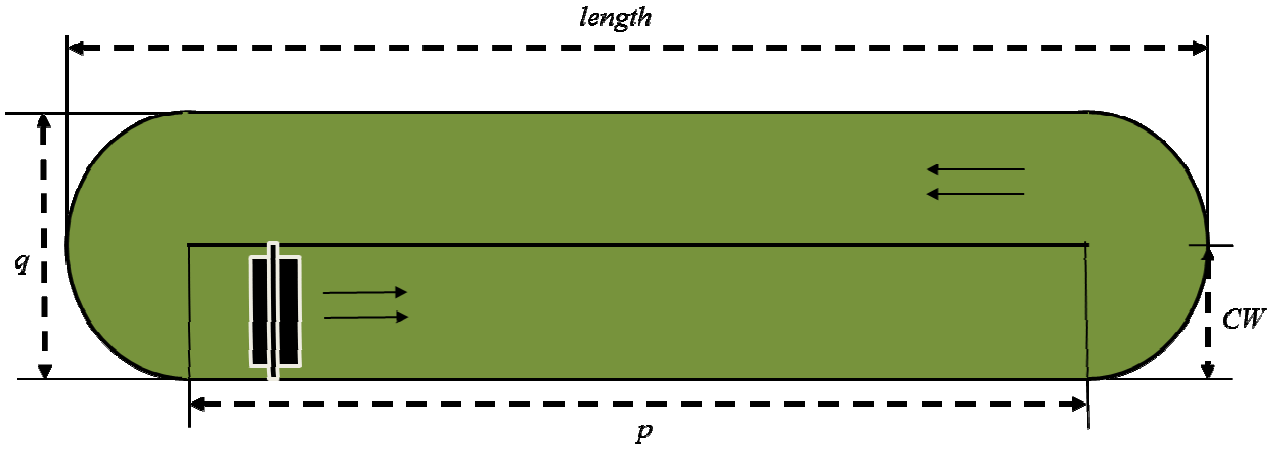
Optimization

Optimization focuses on finding the best solution from a set of available alternatives subject to constraints.



To minimize the cultivation costs of algae oil by designing optimal cultivation systems

Raceway Pond Cultivation Technology



CD = Pond depth

CW = Channel width

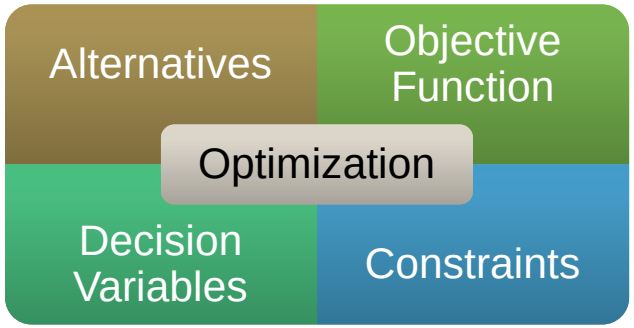
length = Pond length

p = Channel length

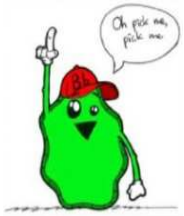
q = Pond width

Alternatives

- Small capital investment
- Free solar energy
- Easy maintenance
- Lower energy requirements

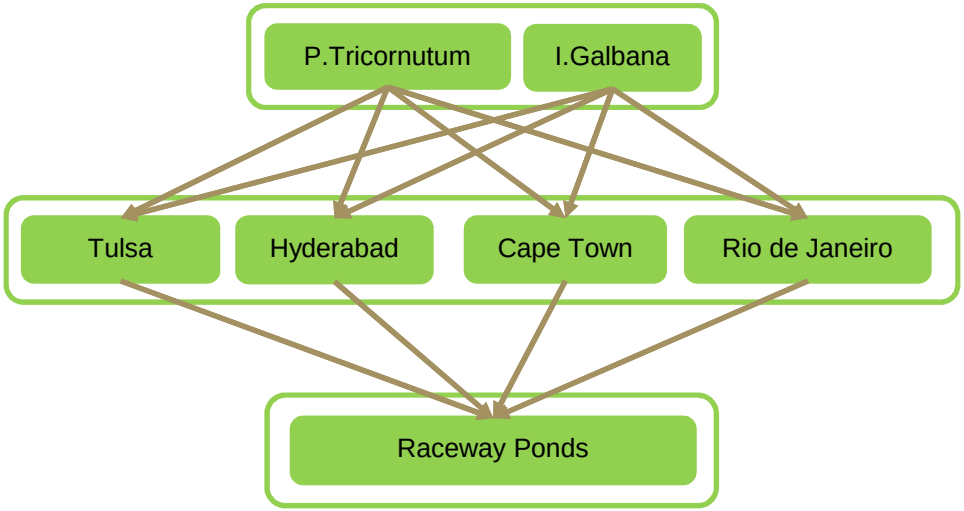


Algae strain



Location

Cultivation

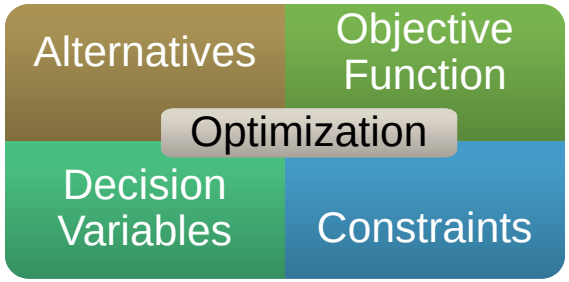


Variation

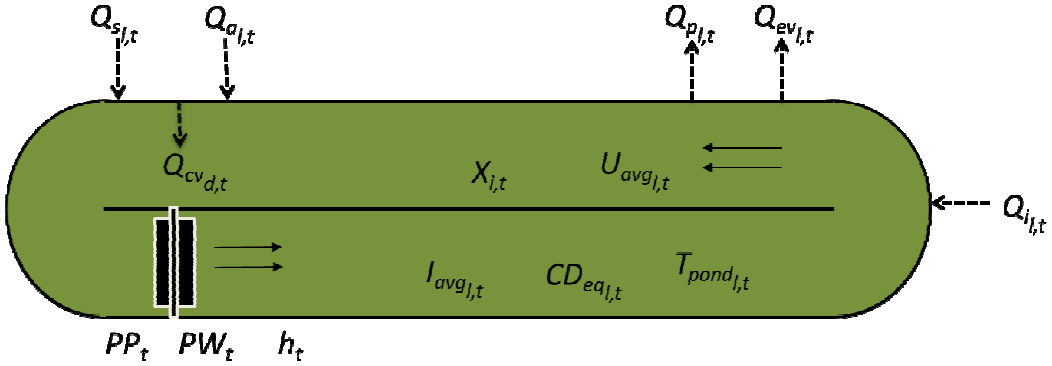
- Growth rate
- Oil content
- Productivity

- Latitude
- Longitude
- Sunlight

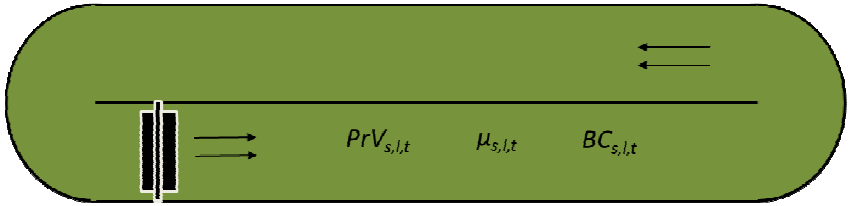
Decision Variables



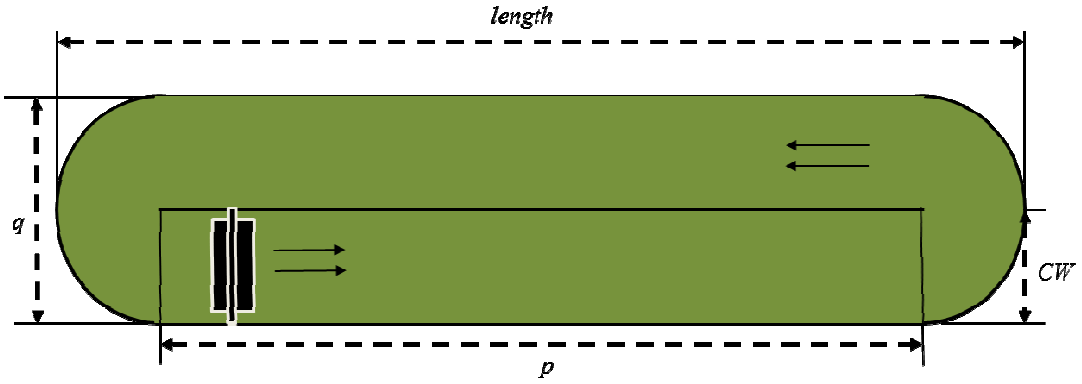
Physical Properties



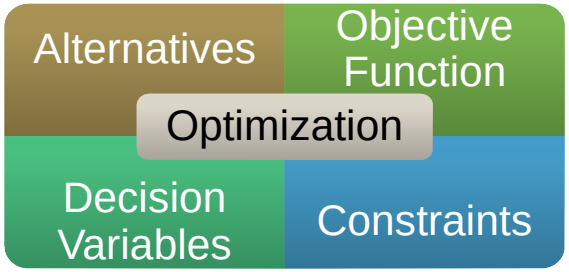
Culture Properties



Design Properties

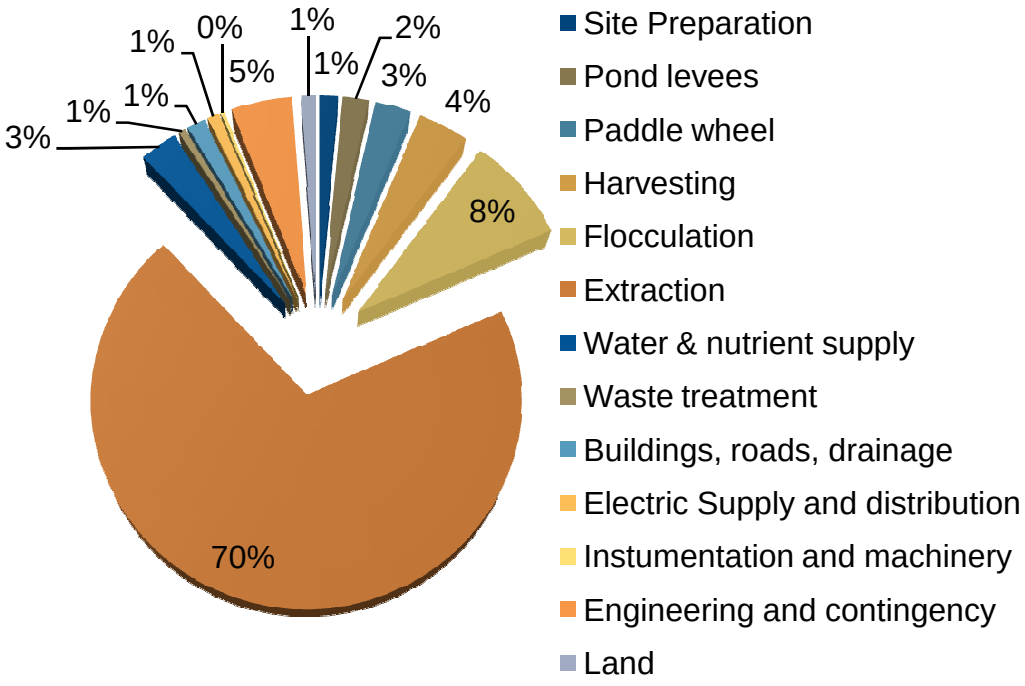


Formulation

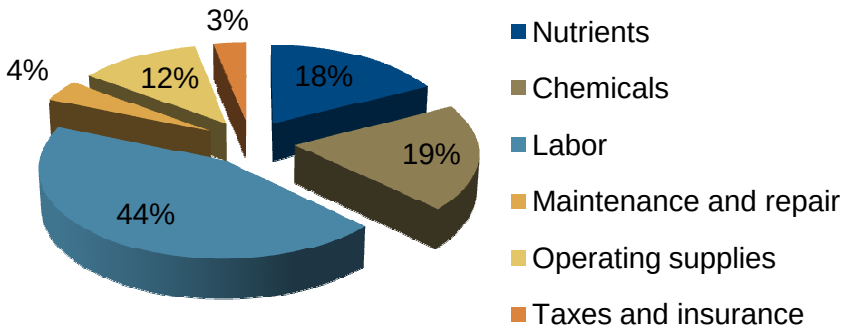


$$\text{Min}\, Z = CpCt + \sum_{n=0}^{10} \frac{1}{(1+MARR)^n} \left[\begin{array}{l} ElecticCt + WaterCt + LaborCt \\ + NutrientCt + ChemicalCt \\ + MaintenanceCt \end{array} \right]$$

Capital Costs



Operating Costs

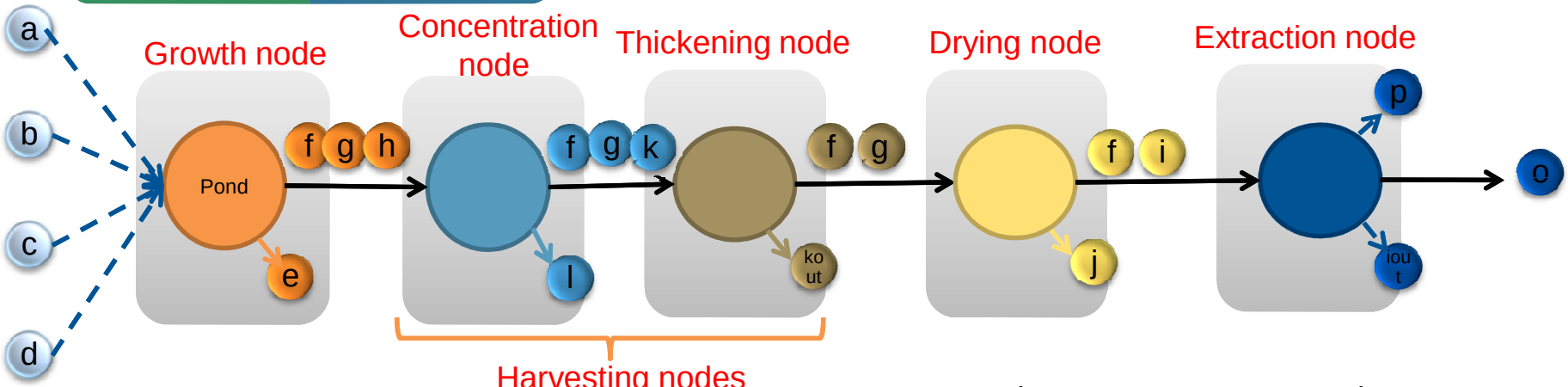


Formulation

Alternatives | Objective Function | Optimization | Decision Variables | Constraints

$$\sum_i \sum_t X_{i,t} = 0 \rightarrow$$ *Mass balance constraint*

$$aCO_2 + bH_2O + cP + gN \rightarrow \overbrace{C_aH_eO_fN_gP_c}^{dry\,algae} + \overbrace{hH_2O}^{water\,in\,algae} + iO_2 + \overbrace{jH_2O}^{wastewater}$$



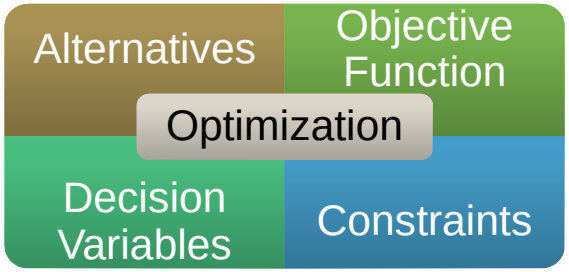
a = carbondioxide inlet
b = water inlet
c = nitrogen inlet
d = phosphorous inlet
e = oxygen outlet

f = dry algae outlet
g = water in algae outlet
h = waste water outlet
k = waste water remain
Kout = waste water remain removed

l = waste water removed
i = water in algae remain
Iout = water remain in algae removed
j = water in algae removed
o = lipid
p = cake

$$\sum_t X_{algaeoil,t} = 1000 \text{ tons/year} \rightarrow$$ *Algae oil demand constraint*

Formulation

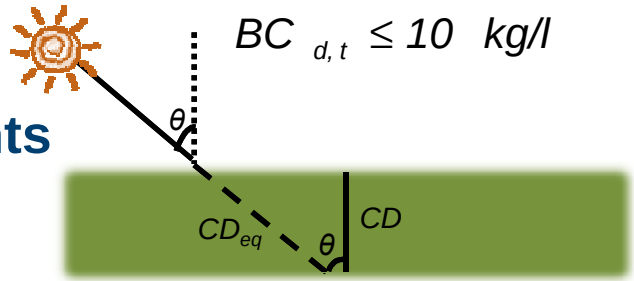


$$0.10 \ m \le CD \le 1 \ m$$
$$CW \le 10 \ m$$
$$0.15 \ m/s \le U_{avg_d} \le 0.30 \ m/s$$
$$BC_{d,t} \le 10 \ kg/l$$

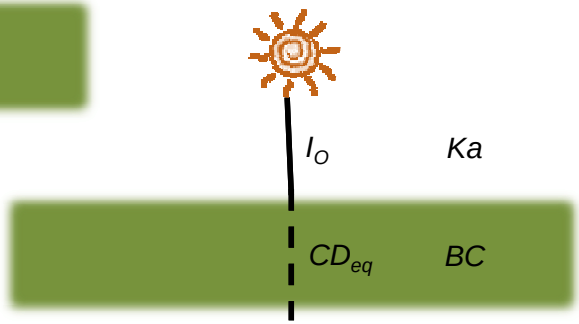
Bound constraints

Location relating constraints

$$CD_{eq_{l,t}} = \left\{ \frac{CD}{\cos(\theta_{l,t})} \right\}$$



$$I_{avg_{l,t}} = \left\{ \frac{I_{O_l} \times [1 - e^{-(CD_{eq_{l,t}} \times Ka_s \times BC_{l,t})}]}{CD_{eq_{l,t}} \times Ka_s \times BC_{l,t}} \right\}$$



$$\mu_{max_{d,t}} = A \times e^{B \times T_{pond_{d,t}}}$$

$$\mu_{d,t} = \left\{ \frac{\mu_{max_{d,t}} \times I^n_{avg_{d,t}}}{I^n_{k_s} + I^n_{avg_{d,t}}} \right\}$$

Relationship b/w culture properties (species) & location

$$PrV_{d,t} = \mu_{d,t} \times BC_{d,t} \rightarrow$$ *Constraint relating productivity and algae species*

Formulation

$$X_{dryalgae,t} = PrV_{l,t} \times V$$

$$\frac{X_{dry\,algae,t}}{X_{WIA,t} + X_{dry\,algae,t}} \times 100 = \%_s$$

$$X_{WW,t} = \left[\frac{X_{dryalgae,\,t}}{BC_t}\right] \times \rho$$

Relationship b/w culture properties, algae species & pond geometry

$$\dot{m}_{out,t} \times Cp \times \left(T_{pond_t} - T_{surr_t}\right) = Q_{p_t} + Q_{s_t} + Q_{a_t} + Q_{ev_t} + Q_{cv_t} + Q_{i_t} \rightarrow$$ *Energy balance constraint*

$$Q_{p_t} = -\varepsilon_w \times \sigma \times T^4_{pond_t} \times SA$$

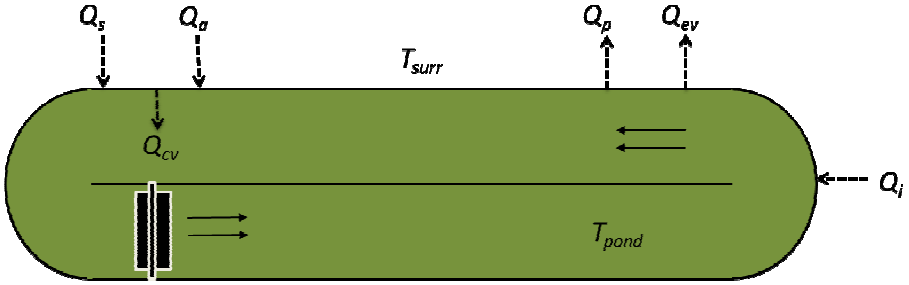
$$Q_{ev_t} = -me_t \times L_w \times SA$$

$$Q_{s_t} = (1 - f_a) \times Io_t \times SA$$

$$Q_{cv_t} = h_{cv_t} \times \left(T_{surr_t} - T_{pond_t}\right) \times SA$$

$$Q_{a_t} = \varepsilon_w \times \varepsilon_a \times \sigma \times T^4_{surr_t} \times SA$$

$$Q_{i_t} = me_t \times SA + X_{WIA,\,t} + (1 - \eta_{recycle}) \times X_{WW,\,t}$$



Formulation

$$h_F = \frac{U_{avg_d}^2 \times RC^2 \times length}{D_h^{\frac{4}{3}}} \qquad h_k = \frac{K \times U_{avg_d}^2}{2 \times g} \qquad h_T = h_F + 2 \times h_K$$

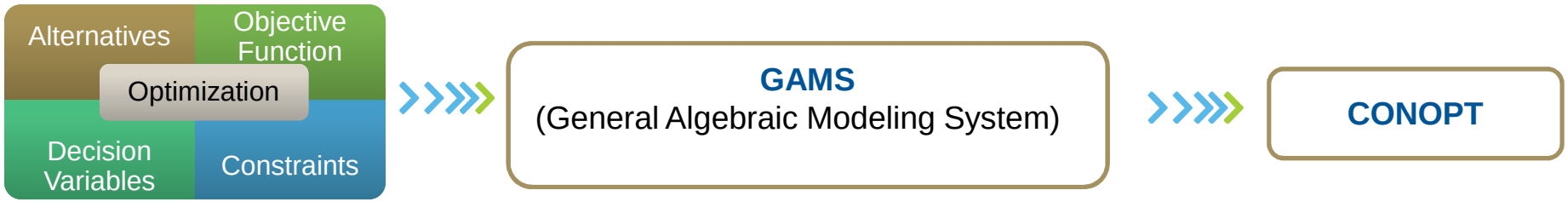
$$PP_{d,t} = \frac{\dot{m}_{out,d,t} \times g \times h_T}{\eta_{PW}} \qquad PW_{d,t} = \frac{2 \times \left[(me_{d,t} \times SA) + X_{WIA,d,t} + (1 - \eta_{recycle}) \times X_{WW,d,t}\right] \times \mu \times length \times (2 \times CD + CW)^2}{\rho^2 \times CD^3 \times CW^3}$$

Power Constraints

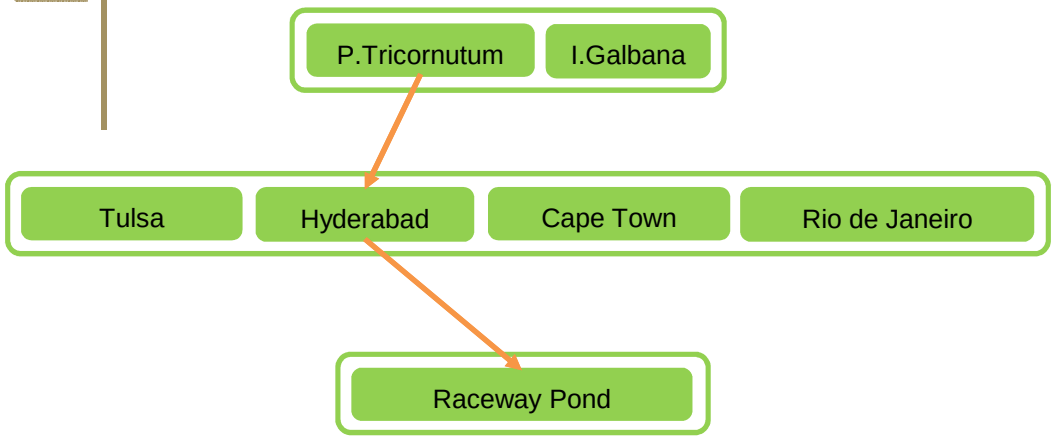
$$Adwater = \frac{1}{\rho}\left[\sum_d \sum_t me_{d,t} \times SA + \sum_d \sum_t X_{WIA,d,t} + (1 - \eta_{recycle}) \sum_d \sum_t X_{WW,d,t}\right] \rightarrow$$ *Water Constraint*

$$length = CW \times 40 \qquad q = 2 \times CW \qquad SA = \frac{\pi q^2}{4} + p \times q \qquad V = SA \times CD \qquad CW = \frac{\dot{m}_{out,t}}{\rho \times CD \times U_{avg_t}}$$

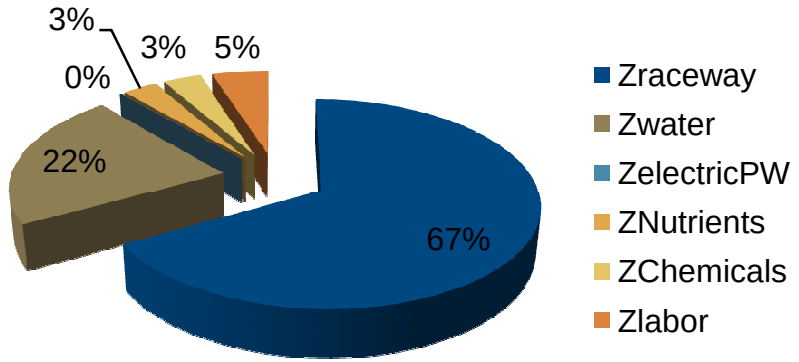
Design Constraints



Results



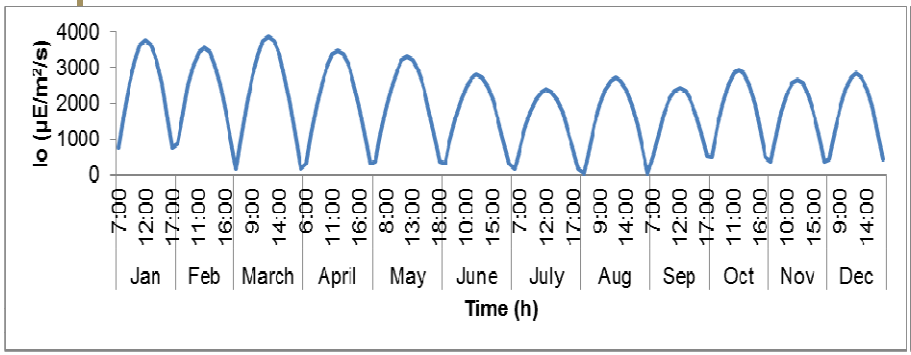
Production Costs

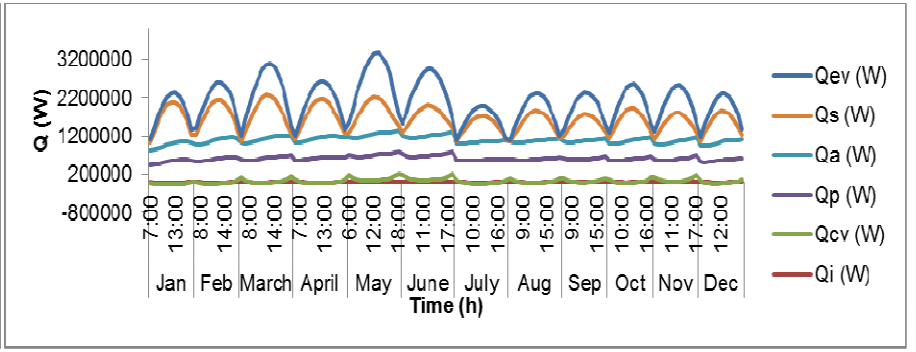


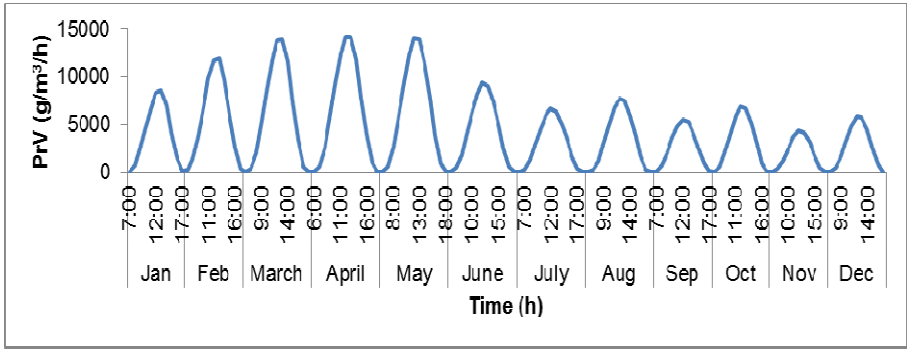
	Z ($)	Depth (m)	Width (m)	Length (m)	V (m^3)	SA (m^2)	I_{avg} (µE m^{-2} s^{-1})	Uavg (m s^{-1})	BC (g l^{-1})	µ (h^{-1})	PrV (g m^{-3} h^{-1})	T_{pond} (C)
1	275,383	0.103	5.45	217.92	242	2349	43	0.108	5.24	0.324	2381	21
2	183,454	0.105	4.07	162.80	138	1311	44	0.109	7.26	0.478	4185	28
3	347,304	0.104	6.29	251.46	326	3128	45	0.104	4.59	0.278	1771	19
4	236,427	0.100	4.95	198.01	194	1939	42	0.104	5.89	0.389	2974	26
5	423,761	0.100	7.08	283.10	396	3964	56	0.133	4.29	0.334	2148	21
6	227,540	0.100	4.73	189.15	177	1770	51	0.144	6.74	0.602	4811	28
7	662,802	0.118	9.07	362.75	770	6509	61	0.122	3.07	0.251	1106	19
8	341,389	0.100	6.22	248.96	307	3066	52	0.134	4.90	0.438	2777	26

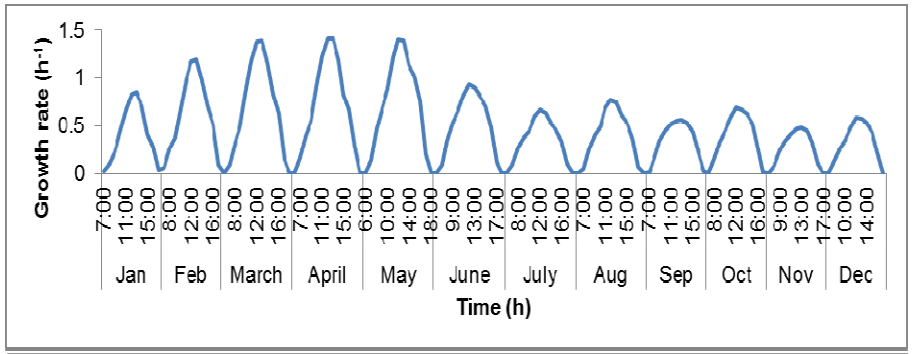
Total cost of producing about 1000 tons/year of algae oil = $ 0.062 per gallon

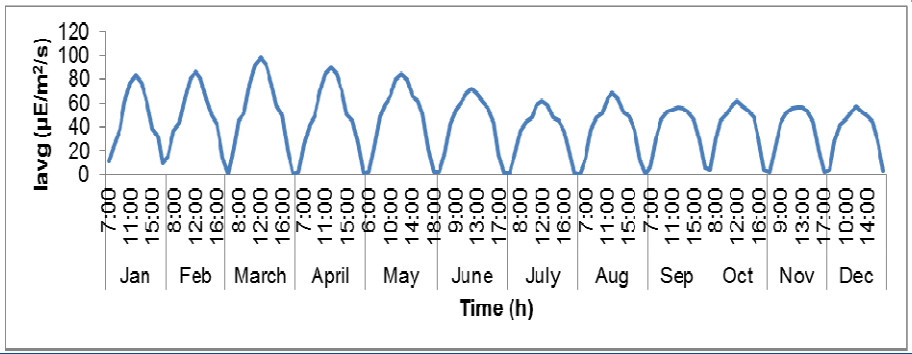
Results

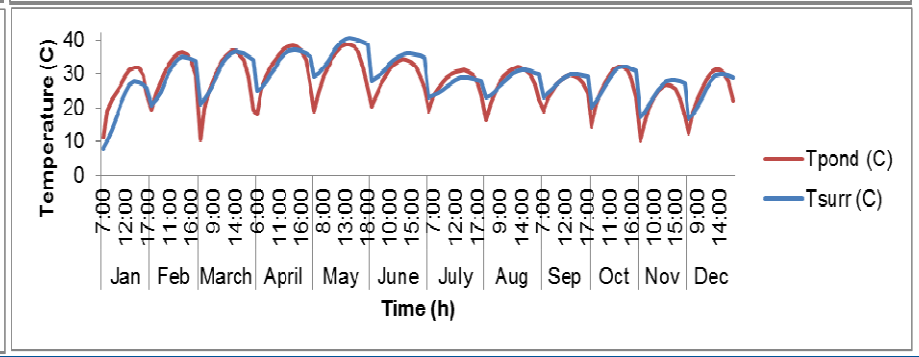

Io (μE/m²/s)
4000
3000
2000
1000
0
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)


Q (W)
3200000
2200000
1200000
200000
-800000
Qev (W)
Qs (W)
Qa (W)
Qp (W)
Qcv (W)
Qi (W)
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)


PrV (g/m³/h)
15000
10000
5000
0
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)


Growth rate (h⁻¹)
1.5
1
0.5
0
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)


Iavg (μE/m²/s)
120
100
80
60
40
20
0
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)


Temperature (C)
40
30
20
10
0
Tpond (C)
Tsurr (C)
Jan Feb March April May June July Aug Sep Oct Nov Dec
Time (h)

Sensitivity Analysis

Sensitivity Analysis -1 (Variation in pond depth)

	Z ($)	Depth (m)	Width (m)	Length (m)	V (m^3)	SA (m^2)	I_{avg} (μE m^{-2} s^{-1})	Uavg (m s^{-1})	BC (g l^{-1})	μ (h^{-1})	PrV (g m^{-3} h^{-1}	T_{pond} (C)
2	183,454	0.105	4.07	162.80	138	1311	44	0.109	7.26	0.478	4185	28
9	198,838	0.300	4.20	167.91	418	1395	26	0.100	4.65	0.265	1379	29
10	213,816	0.500	4.33	173.25	742	1485	20	0.100	3.70	0.198	777	29

Sensitivity Analysis -2 (Variation in recycle efficiency)

	Z ($)	Depth (m)	Width (m)	Length (m)	V (m^3)	SA (m^2)	I_{avg} (μE m^{-2} s^{-1})	Uavg (m s^{-1})	BC (g l^{-1})	μ (h^{-1})	PrV (g m^{-3} h^{-1}	T_{pond} (C)
11	424,689	0.100	4.14	165.40	135	1353	38	0.111	10.0	0.426	4262	28
12	298,429	0.100	4.13	165.22	135	1350	38	0.111	10.0	0.427	4272	28
2	183,454	0.105	4.07	162.80	138	1311	44	0.109	7.26	0.478	4185	28

Sensitivity Analysis -3 (Variation in length/width ratio)

	Z ($)	Depth (m)	Width (m)	Length (m)	V (m^3)	SA (m^2)	I_{avg} (μE m^{-2} s^{-1})	Uavg (m s^{-1})	BC (g l^{-1})	μ (h^{-1})	PrV (g m^{-3} h^{-1}	T_{pond} (C)
13	183,319	0.105	5.79	115.72	137	1310	44	0.100	7.26	0.479	4198	28
2	183,454	0.105	4.07	162.80	138	1311	44	0.109	7.26	0.478	4185	28
14	183,585	0.105	3.32	199.06	138	1311	43	0.119	7.26	0.477	4171	28

Conclusions

- A mathematical framework is developed to estimate the best combination of algae species, geographical location, and raceway pond geometry by combining experimentally validated temperature, irradiance, and algae growth models with optimization
- In order to represent the actual behavior of the outdoor raceway pond, the current model takes into account the diurnal pattern of sunlight, temperature fluctuations, the dynamic behavior of solar zenith angle, and mixing which makes it more realistic compared to the other models in the literature
- This method enables to record the change in culture properties such as biomass concentration, productivity, and growth rate over time

Future directions

- Model the dynamic behavior of algae biomass cultivation and biodiesel production using HYSYS simulation software
- Model the network flow topology of algae oil distribution in the United states

Acknowledgement

- TUPSE Research Group
- Department of Chemical Engineering, The University of Tulsa

Total cost of producing about 10,000 gallons/day of biodiesel = $0.062/gallon

THANK YOU

Questions???