Emergy of Algae Systems Revisited: Comparisons of Algal-Based Wastewater Treatment Systems

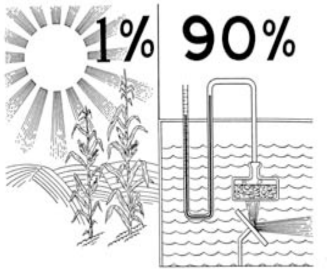
David M. Blersch (1), Walter Mulbry (2), and Patrick Kangas (1)

(1) Biological Resources Engineering Department, University of Maryland, College Park, Maryland, 20742

(2) Beltsville Agricultural Research Center, United States Department of Agriculture, Beltsville, Maryland 20705

Introduction: Early Algal Studies

After World War II, there was a high level of interest in using algal systems in bioengineering designs. Much of this interest was stimulated by the development of the space program where algae were being examined for use in bioregenerative life support systems. Algae strongly influence gas dynamics through photosynthesis, absorbing and releasing CO_2 and O_2 through their metabolism. A variety of laboratory studies with algal bioengineering were undertaken that demonstrated high and efficient levels of photosynthesis under artificial light conditions. In some cases the magnitudes of photosynthesis were higher than found in nature, which lead some researchers to imagine that algae might provide an important source of food for humans.



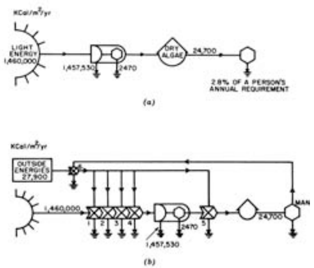
Early conceptual diagram of anticipated photosynthetic efficiency of algal systems that, at the time, was hoped to lead to high-yield food production systems. However, researchers did not adequately account for all energy inputs to their laboratory experiments, as later shown by Odum.

Fallacy and H.T. Odum

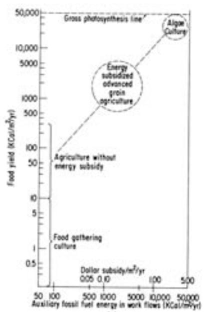
At the same time that the early algal studies were being undertaken, H.T. Odum was developing field techniques and making measurements of primary productivity (photosynthesis at the scale of the ecosystem) in a number of different systems. When he learned of the lab studies he became alarmed at the projection of algal yields that were being made in terms of potential food production (Fisher 1961). Odum called the projections "fallacious dreams" and he exclaimed:

"A cruel illusion was proffered by laboratory scientists and writers who proposed that we could feed the world on algae which they implied were productive on a different order of magnitude from agriculture" (Odum 1971).

To evaluate some of the fallacy with the lab projections, he developed one of the first examples of energy analysis (before energy quality correction) by including the purchased energy subsidies.



Early energy circuit diagram developed by H.T. Odum to analyze the energy flows involved in proposed food-producing algal plants (Odum 1971). Top diagram (a) shows the production with energy costs of management omitted, the basis for the "fallacious" claims of high productivity. Lower diagram (b) shows Odum's correction to the analysis by including all the energy costs of management.

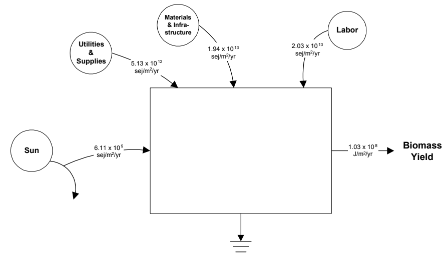


Net food yield to man as a function of the subsidy of fossil-fuel industry, as reported by Odum (1971). Despite reported high productivity, algae culture is seen to be no more efficient (yield per unit energy input) than energy-subsidized grain agriculture. Within this context, since algae culture gives no net increase in production efficiency, early claims of algae production to solve world hunger problems are seen as misguided.

H.T. Odum's Early Energy Calculation

In Odum's original energy analysis he used a literature reference that included some economic cost values of a potential algal pilot plant experiment (Fisher 1961). He converted these dollar costs into energy by multiplying by an energy-to-dollar ratio (10,000 Cal of fossil fuel/$ spent) in order to quantify the energy subsidy. He then compared the algal system to other agricultural systems, with reference to energy subsidy vs. yield.

We re-evaluated Odum's original analysis with more recent approaches of emergy analysis (Odum 1996), as shown in the accompanying energy circuit diagram, tables and footnotes. The total emergy input to the algal pilot plant was 4.5 x 10^{13} sej/yr and the dominant inputs were from labor and materials/infrastructure. Based on the projected yield of the plant, the transformity of algae was 4.3 x 10^5 solar emjoules/J.



Energy circuit diagram used to reanalyze H.T. Odum's analysis of a pilot-scale algae plant for food production.

TRANSFORMITY CALCULATIONS

INPUTS

Note	Item	Data	Units	Emergy (sej / m^2 / yr)	% of Total
1	Solar Insolation	1.46E+06	kcal / m^2 / yr	6.11E+09	0.01%
2	Materials/Infrastructure	1.227	$ / m^2 / yr	1.94E+13	43.27%
3	Labor	1.284	$ / m^2 / yr	2.03E+13	45.27%
4	Utilites& Supplies	0.325	$ / m^2 / yr	5.13E+12	11.45%
	TOTAL (sej / m^2 / yr)			4.48E+13	

OUTPUTS

Note	Item	Data	Units	Emergy (J / m^2 yr)
5	Algal Biomass	4932	g / m^2 / yr	1.03E+08

NOTES

1. Given by Odum (1971) as 1.46 x 10^6 kcal/m^2/yr, where 1 kcal = 4184 sej.

amortization over life span of 10 years, added with materials costs for daily operation. Transformed using 15.8 x 10^{12} sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).

3. Calculated from labor costs for 100-acre facility as reported in Fisher (1955), assuming 1/3 of initial investment costs is for installation labor, added to total for engineering labor, all amortized over life span of 10 years. This is then added with daily operating labor cost. Transformed using 15.8 x 10^{12} sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).

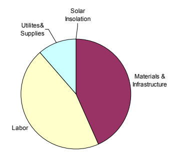
4. Calculated from utilities and supplies costs for daily operation of 100-acre facility as reported in Fisher (1955). Transformed using 15.8 x 10^{12} sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).

5. Calculated from projected net algae productivity of 20 t/acre/yr as reported in Fisher (1955), and adjusted assuming gross productivity is 10% greater (Odum (1971)). Used heat value of biomass of 5 kcal/g given in Figure 4-10, p. 127 in Odum (1971).

TRANSFORMITY

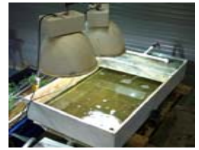
Transformity (T) = Σ(Inputs) / Σ(Outputs)

T = 4.34E+05 sej/J

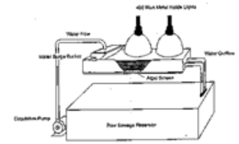


Percent of total energy inputs for algal food production facility analyzed by Odum (1971).

Algal Wastewater Treatment Technologies

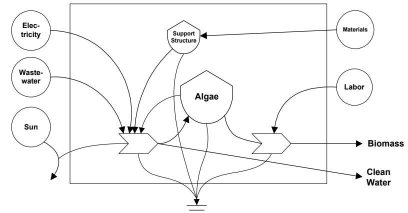


Lab-scale algal turf scrubber operating at the University of Maryland.



Schematic representation of a recirculating algal turf scrubber.

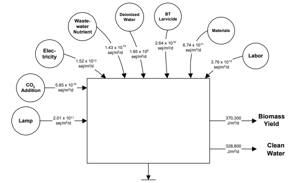
Algal systems continue to be useful in bioengineering designs. One important use is for wastewater treatment. Pollutants are taken up or metabolized by algal communities and they can be removed from the water source when algal biomass is harvested from the system. An example of this kind of system is the algal turf scrubber, shown in the figures above. In this system polluted water is passed through a trough containing a film of benthic algae. Harvest of the algae improves water quality since pollutants are advected from the system. The generalized energy circuit diagram of an algal turf scrubber is included below. Note that although the system is designed to treat wastewater, there are actually two outputs: clean water and algal biomass.



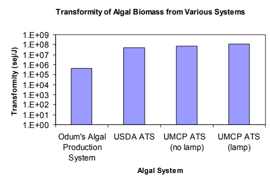
Energy circuit diagram of an algal turf scrubber.

Comparison of Analyses

We evaluated three experimental studies of algal turf scrubbers with emergy analysis. Overview energy diagrams were developed for systems with artificial lighting and sunlight at the University of Maryland at College Park (UMCP) and one at USDA agricultural research lab in Beltsville, Maryland, which also utilizes artificial lighting. Transformities for algal biomass are shown in the chart. Odum's original analysis of the algal pilot plant is also shown for comparison, though this system was not designed for wastewater treatment. All of the algal turf scrubber transformities are similar, demonstrating the interesting result that transformity is not qualitatively affected by the use of alternative light sources (sunlight vs. artificial lighting with electrical lamps).



Energy circuit diagram of the USDA algal turf scrubber, used to calculate the transformity of the outputs. Similar diagrams were developed for the UMCP algal turf scrubber with and without artificial lighting.



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Conclusions

H.T. Odum's original energy analysis of an algal pilot plant is historically important. It represents one of the first examples of energy analysis, which was later revised with corrections for energy quality. Odum's analysis quantified the magnitudes of energy subsidies to a biomass yield system that had previously been ignored in assessments of the system. The analysis also exposed some incorrect thinking about the performance of the system that could have lead to inappropriate policy advocating algal agriculture.

In fact, algal systems for food production have never developed, perhaps for the reasons Odum studied. However, wastewater treatment applications are being studied that have potential for economic development. One benefit of systems such as the algal turf scrubber is that they have byproducts of both clean water and algal biomass. Interestingly, both of these byproducts have similar transformities as calculated for the USDA system shown above (6.03 x 10^7 sej/J for clean water and 5.36 x 10^7 for algal biomass).