

MSc Architecture: Advanced Environmental and Energy Studies

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CAN HUMAN SEWAGE PROVIDE THE FEEDSTOCK FOR
BIODIESEL PRODUCTION BY PHOTOAUTOTROPHIC
MICROALGAE?

Word Count 2179

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For the attention of Melissa Taylor

January 11th 2009

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Introduction

This essay relates to the lecture 'Sewage treatment' of Module A3.

Human sewage consisting of urine, faeces and home wastewater is a nutrient rich liquid which when discharged in the wrong place becomes a serious pollutant causing environmental damage and human health problems.

Photosynthetic algae require sunlight, CO₂ and nutrients in order to grow and multiply. Certain strains of algae produce high quantities of oil that is suitable for refining into biodiesel.

The purpose of this essay is to examine whether it is feasible to use sewage to produce biodiesel.

Sewage pollution

In the developed world most sewage is treated prior to discharge into the environment. This is seldom the case in the developing world, with much of the sewage entering the world's oceans (UNEP¹, 2006).

The UNEP report into the state of the marine environment states that '*Discharge of untreated domestic wastes is a major source of marine pollution, and perhaps the most serious problem within the framework of the gpa*².' This causes eutrophication and algal blooms. In East Asia 89% of sewage is discharged untreated, while 53% of wastewater entering the Mediterranean is untreated (2006).

The economic loss associated with pathogenic microorganisms from land-based wastewater pollution of the sea has been estimated to be us\$12 billion per year and that globally **an additional** us\$56 billion is needed for wastewater treatment (UNEP, 2006).

Not all untreated sewage is discharged to the sea immediately. Pearce, F stated that a tenth of the world's irrigated crops are watered by untreated sewage. The

¹ United Nations Environment Programme The report was commissioned by the Coordination Office of the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (gpa) of the UNEP.

² Global Programme of Action.

pathogen-laden sewage is also rich in nitrates and phosphates leading to good crop yield (2004).

However the WHO³ states that '*about 1.5 million deaths per year from diarrhoeal diseases are attributable to poor sanitation and hygiene.*' (2006).

The problem with conventional biofuels

In 2007, to help combat climate change caused by the burning of fossil fuels, the European Commission proposed that by 2020 at least 10% of transport fuels should be biofuels (Brahic, C 2008). In December 2007 about 12 million hectares were used to grow biofuels including palm oil for biodiesel. Biofuels were promoted as carbon-neutral fuels that could mitigate climate change. This was misleading. Rainforest is destroyed and biofuel crops require huge amounts of irrigation water and fertilizers. Fossil fuels are required to produce these fertilisers and the greenhouse gas nitrous oxide released by during fertiliser use has a CO₂E⁴ of over 300 (Pearce, F. et al 2007). Nowak, R stated that '*biofuels made from food crops such as corn and palm oil have driven up food prices and depleted rainforests, often without reducing net greenhouse emissions.*' (2008).

Producing biodiesel from microalgae need not compete for land with food crops or destroy rainforests. If sewage was used as a culture medium it may not require the addition of nitrogen or phosphate fertilizer.

³ World Health Organisation

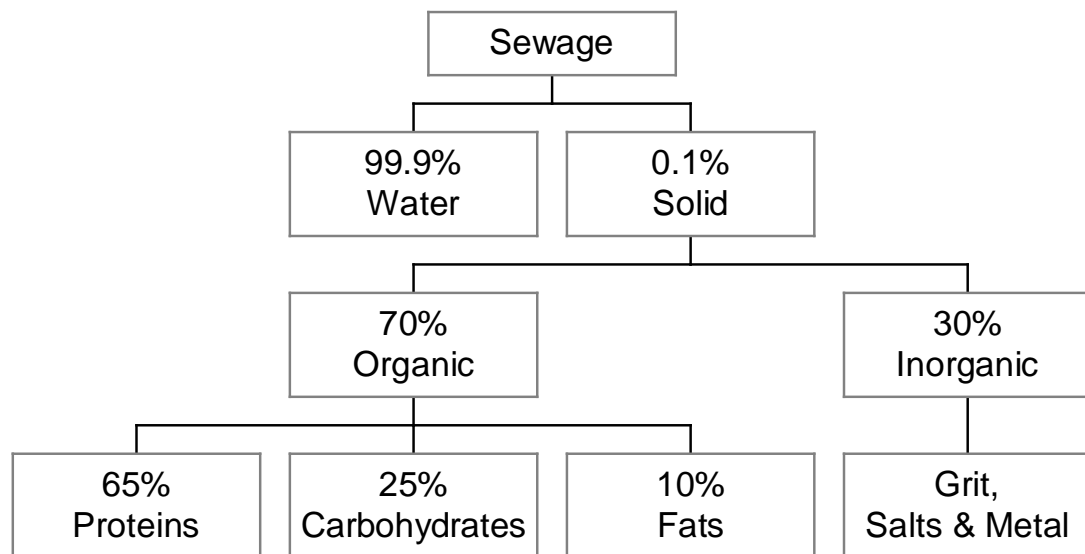
⁴ Carbon dioxide equivalent

Critical Analysis

Composition of sewage

Microalgae have certain nutritional requirements, so it is important to consider the composition of sewage. Grant, N et al describe domestic sewage as '*a mixture of water and the various types of organic matter ...; faeces and urine, food scraps, hair and toilet paper*' as well as various chemicals and detergents (2005).

Figure 1 – Composition of Sewage.



Source: Tebbutt, 1998 cited in Mara, D 2004, p.3

Table 1 shows that most of the nutrients produced by a human are in the urine and that in healthy people urine is sterile.

Table 1 – Average statistics for urine and faeces

Per adult per day	Faeces	Urine
Quantity	135 - 270g/day wet weight	1000 – 1,500g/day wet weight
	35 – 70g/day dry matter	50 – 70g/day dry matter
Water Content	66 – 80%	93 – 96%
Contents	Typical daily yield	Typical daily yield
Nitrogen (N)	3g	8g
Phosphorus (P)	2g	2g
Potassium (K)	1g	2g
Calcium (Ca)	2g	2g
C:N Ratio	8:1	1:2
N:P Ratio	1.5:1	4:1
Pathogens	100 – 400 billion coliforms Enterococci Streptococci	None in normal circumstances

Source: Harper, P. and Halestrap, L. 1999

In her book Liquid Gold, Steinfeld, C suggests that the nutrient content of greywater is insignificant compared to urine and faeces (2004).

The nutrient levels in sewage, urine and faeces vary across the world due to diet.

Table 2 compares urine from a Swedish⁵ and Zimbabwean⁶ study.

Table 2– Actual statistics for urine⁷

Parameter		Nitrogen (N) g/day		Phosphorus (P) g/day		Potassium (K) g/day	N:P Ratio
Ekoporten (Sweden)		10.14		0.93		3.26	10.88 :1
Gebers (Sweden)		10.49		0.68		2.25	15.32 :1
Swedish Mean		10.32		0.81		2.75	12.76 :1
Sample ID (Zimbabwe)	Ammonia (NH3) in 100ml of urine (g)	Nitrogen (N) g in 1.25 litre ⁸	Phosphorus (P) g in 100ml of urine	Phosphorus (P) g in 1.25 litre ⁹	Potassium (K) in 100ml of urine	Potassium (K) g in 1.25 litre ¹⁰	N:P Ratio
Farmer 1	0.24	2.5	0.0127	0.15875	0.091	1.1375	15.7:1
Farmer 4	0.35	3.6	0.01207	0.150875	0.085	1.0625	23.9:1
Farmer 2	0.2	2.1	0.0037	0.04625	0.086	1.075	45.4:1
Farmer 5	0.2	2.1	0.00945	0.118125	0.058	0.725	17.8:1
Farmer 3	0.19	2	0.0124	0.155	0.079	0.9875	12.9:1
Farmer 6	0.28	2.9	0.003	0.0375	0.088	1.1	77.3:1
Zimbabwean mean	0.24	2.5	0.0127	0.15875	0.091	1.1375	15.7:1

Source: Vinneras, B. 2002 and Guzha, E. 2002

The average Swede's urine contained 4 times the nitrogen and 5 times the phosphorus as the average Zimbabwean.

Both studies concluded that separating urine and faeces was a more efficient way of recycling the nutrients for crop plant growth. But what about for growing microalgae?

⁵ Björn Vinnerås of the University of Agricultural Engineering, Sweden investigated the possibilities for sustainable nutrient recycling by faecal separation combined with urine diversion.

⁶ Guzha, E of the Mvuramanzi Trust (a non-profit that helps rural families manage water and sanitation) Zimbabwe investigated the effects of humanure and ecofert (urine) on soil fertility and physical properties.

⁷ The studies did not quote nutrient levels in faeces.

⁸ Based on an estimate of average urine production of 1.25 litres.

⁹ As above

¹⁰ As above

Nutritional requirements of photoautotrophic microalgae

Photoautotrophic microalgae are photosynthetic organisms that use sunlight to convert CO₂, water and nutrients to body tissue, releasing oxygen in the process. 1g of algae fixes 0.52 g carbon and produces 1.55g of oxygen¹¹ (Mara, D 2004) incorporating 0.0922g¹² of nitrogen and 0.0127g of phosphorous¹³. Thus the ratio of nitrogen to phosphorus in algal tissue is 7.25:1. From table 1, the ratio in urine and faeces is 4:1 and 1.5:1 respectively.

Low-tech wastewater treatment using photoautotrophic microalgae

The role of microalgae in wastewater treatment via WSPs¹⁴ has been well documented by Duncan Mara¹⁵. WSPs are '*large shallow basins enclosed by earth embankments where raw wastewater is treated by natural processes involving algae and bacteria.*' (Mara, D 2004).

Naturally occurring microalgae supply the oxygen needed by the pond bacteria to oxidize the wastewater BOD¹⁶. The algae assimilate the CO₂ produced by the bacteria (Mara, 2004). No additional CO₂ is added which limits the treatment rate. Currently algae are not usually harvested from WSPs, but research undertaken by Benemann, J et al showed that there are enough nutrients available in treatment-pond sewage to grow and harvest two crops of algae before the nitrogen is depleted. Then, due to the excess phosphates further crops of algae can be grown by the addition of nitrogen fixing microalgae. The limiting factor is CO₂, which must be supplied for high rates of cultivation (Sheehan, J et al 1998, citing the work Benemann, J et al).

¹¹ Based on molar mass calculations

¹² 8g N to 2g P

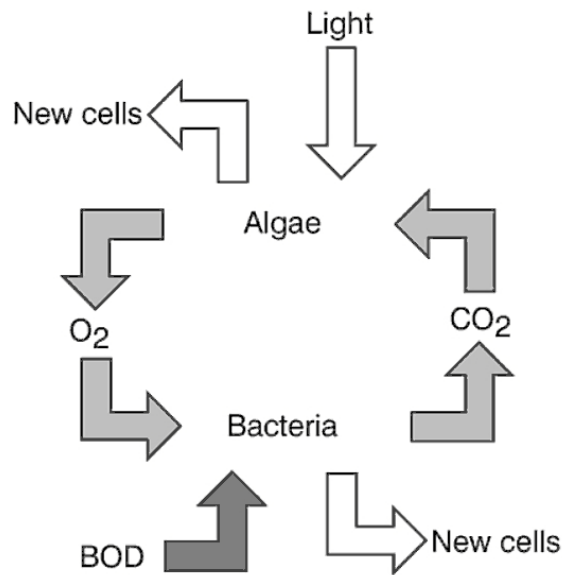
¹³ $106\text{CO}_2 + 236\text{H}_2\text{O} + 16\text{NH}_4^+ + \text{HPO}_4^{2-} \xrightarrow{\text{light}} \text{C}_{106}\text{H}_{181}\text{O}_{45}\text{N}_{16}\text{P} + 118\text{O}_2 + 171\text{H}_2\text{O} + 14\text{H}^+$ (Mara, D 2004).

¹⁴ Waste stabilization ponds

¹⁵ Professor of civil engineering at the University of Leeds

¹⁶ Biochemical oxygen demand

Figure 3 – Algal-bacterial Mutualism in Facultative and Maturation WSP Ponds



Source: Mara, 2004

Commercial production of microalgae

The current large-scale production of algae is for the health-food market. Spolaore, P¹⁷ et al found that microalgae can have high protein levels and be highly nutritious foodstuffs (2005).

Table 3 - General composition of different human food sources and algae (% of dry matter)

Commodity	Protein	Carbohydrate	Lipid
Meat	43	1	34
Milk	26	38	28
Rice	8	77	2
Soybean	37	30	20
<i>Chlorella vulgaris</i>	51–58	12–17	14–22
<i>Dunaliella salina</i>	57	32	6
<i>Scenedesmus obliquus</i>	50–56	10–17	12–14
<i>Spirulina maxima</i>	60–71	13–16	6–7
<i>Synechococcus sp.</i>	63	15	11

Source: Spolaore, P

¹⁷ École centrale Paris

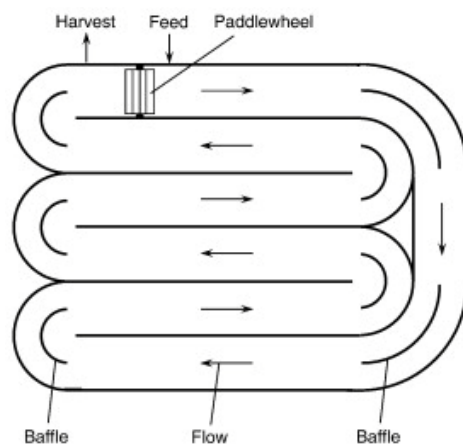
Large-scale production of microalgae requires the use of either raceway ponds or photobioreactors.

Raceway ponds

A raceway pond, which is used in 98% of commercial operations, is a looped channel about 30cm deep in concrete or compact earth. A paddlewheel continuously mixes the water. The culture is fed nutrients in front of the paddlewheel and harvested behind it. Raceways cost much less than photobioreactors to build and operate but have a lower productivity, and the algae are prone to contamination by other species and predation and therefore often sited in remote locations¹⁸ (Chisti, Y 2007).

Because CO₂ is a limiting factor to algal growth it is pumped into the water (Earthrise, 2004)

Figure 5 – Raceway pond (Arial View)



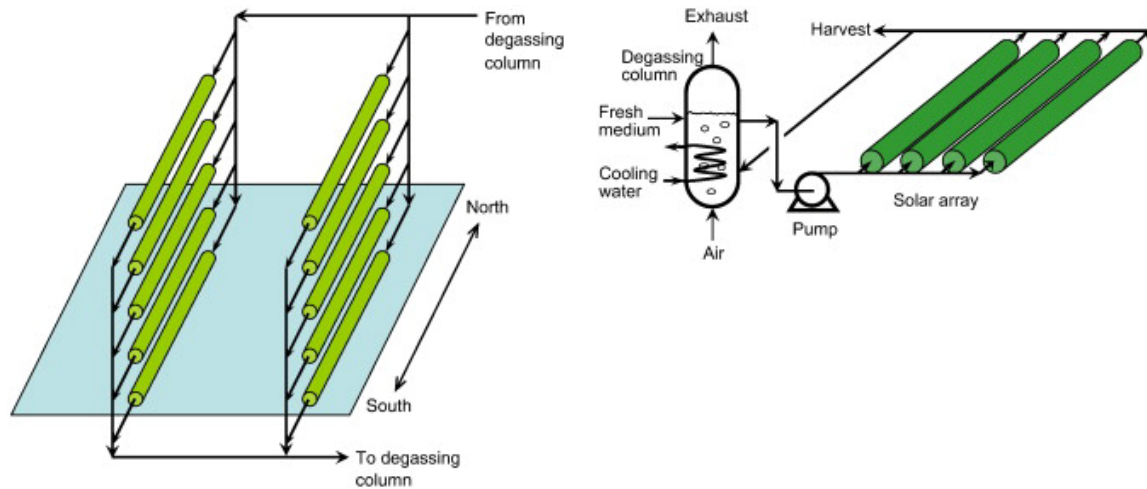
Source: Chisti, Y 2007

Photobioreactors

Photobioreactors allow single-species culture of microalgae. Tubular photobioreactors consist of a solar collector to capture sunlight: an array of straight transparent plastic or glass tubes. Like raceway ponds, continuous culture operates (Chisti, Y 2007).

¹⁸ See [appendix 1](#)

Figure 6 – A fence-like solar collector and a tubular photobioreactor with parallel run horizontal tubes.



Source: Chisti, Y 2007

There are numerous designs based on the photobioreactor idea used by various start-up biofuel companies, but they are all essentially attempting the same thing – a high rate of continuous culture of a single species of algae in a closed system.

Separating urine and faeces

Urine is the most nutrient rich part of human excreta and the safest to handle.

The author found no literature on the use of photobioreactors¹⁹ to handle raw sewage, but using urine as a growth medium is documented. Nutrient recycling is vitally important on space stations. Yang, C²⁰ et al investigated the use of *Spirulina platensis* to treat human urine as part of a BLSS²¹ and found that algae in batch culture could consume 99% and 99.9% of the Nitrogen and Phosphorus respectively (2008).

Adamsson, M from the University of Göteborg investigated human urine by greenhouse culturing the microalgae *Scenedesmus acuminatus*. He found that untreated urine, diluted to 2%, could be used as a growth medium and adding trace elements to the urine, like iron promoted algal growth. In this study the algae formed

¹⁹ See section - Raceway ponds and photobioreactors

²⁰ Beijing University of Aeronautics and Astronautics

²¹ Bioregenerative life support system

the bottom of a food chain for fish production via the zooplankton *Daphnia magna*. The urine was initially more productive than the MBL²² and the *Daphnia* could not survive initially, but he concluded that urine could be used to produce algae as the bottom of a food chain for fish production. This inhibition of predation could be used to an advantage in algae farming (2000).

Photoautotrophic microalgal biodiesel

Data sources

Much of the early data on the oil yield of microalgae came from the U.S. Department of Energy's Office of Fuels Development funded Aquatic Species Programme (ASP) that ran from 1978-1996. There have been several university studies since the ASP with peer-reviewed and published data but many unsubstantiated claims by algal-biofuel start up companies.

²² Artificial algal medium

Table 4 – Comparison of the robustness of data presented by some researchers and start-up companies with interests in algal-biofuel.

Researcher(s)	Study(s)	Publication	Robustness of claims
Sheehan, J, Dunahay, T, Benemann, J and Roessler, P Aquatic Species Programme	Numerous	A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae National Renewable Energy Laboratory	Scientists funded by the US government. Results numerous, peer-reviewed and robust. Research concentrated on raceway ponds. More research into using sewage ponds as a feedstock necessary. Programme closed because of falling oil prices.
Bilanovic, D, Andargatchew, A and Kroeger, T (Center for Environmental, Earth, and Space Studies, Bemidji State University, USA) and Gedaliahu Shelef, G (Faculty of Civil and Environmental Engineering – Technion Israel Institute of Technology)	Freshwater and marine microalgae sequestering of CO ₂ at different C and N concentrations – Response surface methodology analysis	Energy Conversion and Management Volume 50, Issue 2, February 2009, Pages 262-267	Post-graduate university research. Results peer- reviewed and published. Still robust, but perhaps less so than the ASP due to limited scale. Research concentrated on photobioreactors. More evidence required.

Researcher(s)	Study(s)	Publication	Robustness of claims
Chisti, Y (Institute of Technology and Engineering, Massey University, New Zealand)	Biodiesel from microalgae	Biotechnology Advances Volume 25, Issue 3, May-June 2007, Pages 294-306	Post-graduate university research. Results peer-reviewed and published. Still robust, but perhaps less so than the ASP due to limited scale. Research compared Raceway ponds and photobioreactors. More evidence required, especially regarding photobioreactors.
GreenFuel Technologies Corporation	Internal corporate research and development	Website claims	Start-up company looking to secure funding from investors. Claims disputed by other researchers ²³ . Empirical data and published papers required to validate claims regarding productivity of proprietary bioreactor.

²³ Dimitrov, K argued mathematically that Greenfuel's claims broke the laws of thermodynamics (2007).

Researcher(s)	Study(s)	Publication	Robustness of claims
Valcent Products Inc	Internal corporate research and development	Website claims	Start-up company looking to secure funding from investors. Claims disputed by other researchers ²⁴ . Empirical data and published papers required to validate claims regarding productivity of proprietary bioreactor.
Aquaflow	Internal corporate research and development	Website claims	Start-up company looking to secure funding from investors capitalists. Modest claims, focussed on proof of concept, not yield. Empirical data and published papers required to validate claims.

²⁴ Benemann, J argued mathematically that Valcent's claims broke the laws of thermodynamics (2008)

Oil yield discussion

Table 5. Oil content of some microalgae

Microalga species	Oil content (% dry wt)
<i>Botryococcus braunii</i>	25–75
<i>Chlorella sp.</i>	28–32
<i>Cryptocodinium cohnii</i>	20
<i>Cylindrotheca sp.</i>	16–37
<i>Dunaliella primolecta</i>	23
<i>Isochrysis sp.</i>	25–33
<i>Monallanthus salina</i>	> 20
<i>Nannochloris sp.</i>	20–35
<i>Nannochloropsis sp.</i>	31–68
<i>Neochloris oleoabundans</i>	35–54
<i>Nitzschia sp.</i>	45–47
<i>Phaeodactylum tricornutum</i>	20–30
<i>Schizochytrium sp.</i>	50–77
<i>Tetraselmis sueica</i>	15–23

Source: Chisti, Y 2007

The focus of the ASP was to produce biodiesel from high lipid-content algae grown in ponds, using waste CO₂ from coal-fired power plants. The early studies used high-rate sewage ponds²⁵, but soon moved on to fresh and marine water ponds with the addition of agricultural fertilizers. The programme concluded that the technology faced many R&D obstacles but in theory 2,000 square kilometres of climatically suitable land areas in the U.S. could produce one quad²⁶ of fuel. (Sheehan, J et al

²⁵ Sewage treatment ponds with additional CO₂

²⁶ One quadrillion (1,000,000,000,000) British Thermal Units (BTU)

1998). From [appendix 2](#) this would indicate 200,000 square kilometres²⁷, could produce the fuel required by the world in 2010.

Some start-up companies such as Greenfuel and Valcent have made audacious claims about the biodiesel productivity of microalgae using their propriety systems. As they are not backed by evidence they will be discussed no further.

²⁷ Less than 10% of the land area of Algeria

Chisti, Y has evaluated the potential of algal-biodiesel and compared it to other crops.

Table 6. Oil yield per hectare of various energy crops.

Crop	Oil yield (L/ha)
Corn (Maize)	172
Soybean	446
Canola (Oil Seed Rape)	1190
Jatropha	1892
Coconut	2689
Oil palm	5950
Microalgae 70% oil (by wt) in biomass Bioreactor produced.	136,900 (based on experimentally demonstrated biomass productivity in photobioreactors. Actual biodiesel yield per hectare is about 80% of the yield of the parent crop oil.)
Estimated yield of microalgae 70% oil (by wt) in biomass Bioreactor produced at 80% of parent crop oil.	109,520
Microalgae 30% oil (by wt) in biomass Bioreactor produced.	58,700 (based on experimentally demonstrated biomass productivity in photobioreactors. Actual biodiesel yield per hectare is about 80% of the yield of the parent crop oil.)
Estimated yield of microalgae 30% oil (by wt) in biomass Bioreactor produced at 80% of parent crop oil.	46,960

Source: Chisti, Y 2007

Benemann, J, calculating the maximum rate of algal growth possible due to photosynthetic limitations came up with a maximum oil yield of 15 metric tonnes/hectare/year = approx 17,000²⁸ litres a year and estimated a possible 34,000 – 51,000 litres a year maximum with GMOs²⁹ or VBRs³⁰ – [see appendix 3](#) (2008).

Bilanovic, D et al, investigating the potential of sequestering CO₂ from fossil fuel power stations with microalgae, suggested that '*Secondary effluents from municipal treatment plants and other industrial effluents could provide water and nutrients (N&P) for MSCO₂*,³¹' and envisaged pipelines transporting CO₂ from PSBFF³² operating in cold regions to MSCO₂ located in warm deserts (2008).

To date the only company that has demonstrated the ability to convert wild algae from effluent management systems to biofuel and power a vehicle is New Zealand based Aquaflow. Although the fuel used was a B5³³ blend (Aquaflow, 2008) it demonstrated proof of concept.

Conclusion

Summary of case the made

The idea of transforming sewage from a problem to a solution is enticing. However, there have been few studies conducted on the specific use of sewage to provide the feedstock for biodiesel production. Even the ASP changed focus from sewage to agricultural fertilizers early in the programme. Since then most commercial and academic research into algal-biodiesel production has concentrated on the growth of the algae in specifically created growing media. However, there is a long history of exploiting algae in WSPs and there has been some promising research on using urine for algae production.

²⁸ Based on a very rough estimate of 1 litre of biodiesel weighing 7.34 g.

²⁹ Genetically modified organisms.

³⁰ Vertical Bioreactors

³¹ Microalgae sequestering of CO₂

³² Power stations burning fossil fuels

³³ 5% biodiesel mixed with petroleum diesel

Perhaps specifically created media should continue to be used while the photobioreactor algal-biodiesel industry reaches maturity, and wastewater harvesting should concentrate on developing biodiesel from wild species from WSPs and raceway ponds.

Meanwhile the problem of sewage pollution, particularly in the developing world must be tackled for the reasons outlined in the introduction, including economic loss. When town planners are considering new infrastructure perhaps this is an opportunity to build high-rate sewage ponds or raceway ponds near fossil fuel power stations and incorporate algal carbon capture.

Existing Orthodoxy

Initially the concept of growing transport fuel instead of burning fossil fuel was welcomed as sustainable. The idea soon lost favour due to problems discussed in the introduction. The arguments for creating biofuels out of algae often cite that they do not compete with land for food production. However Spolaore, P et al showed that microalgae are highly nutritious foodstuffs and Adamsson, M concluded that algae grown in urine could form the basis for an aquaculture food chain. So algal-biofuel is potentially competing with food production.

Another fundamental question is should civilisation continue to use oil for general transportation at all, whether from fossil sources or biofuels. Cheap biofuels may stall research into efficient electric vehicles powered by renewable energy. Maybe biofuels should be restricted for use as aviation or rocket fuel.

Limitations of the essay

This essay has avoided looking at costs of microalgae production.

This essay looked at human sewage and did not consider the aquatic pollution caused by nitrogen and phosphate agricultural fertilizer run-off or animal sewage.

Furthermore the essay did not investigate the potential NOX and SOX³⁴ emissions

³⁴ Oxides of nitrogen and sulphur

from algal-biodiesel, or indeed the opposite: the absorption of NOX and SOX from flue gases by algae.

Finally the essay did not compare land, cost and energy requirements of biodiesel photobioreactors with other forms of alternative fuel, such as using solar thermal to produce electricity.

Further research

Trials need to continue into using wild species of algae from WSP ponds to produce biofuel.

Trials need to be performed to create a growth medium out of both urine and sewage that has undergone primary treatment to remove solids both in raceway ponds and photobioreactors to produce biodiesel. These trials need assess a wide range of algal species and take place using both fresh and seawater as dilutants.

Only results from peer-reviewed academic research can be taken seriously. Claims made by algae biofuel start-ups must be backed by evidence.

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Word Count – 2179

Appendices

Appendix 1 - Commercial algae farming

Until now the main application of farming microalgae has been for a highly nutritious foodstuff. One of the biggest in the world is Earthrise farms' *Spirulina* plant that covers 44 hectares in the Californian desert (P. Spolaore, et al. 2006)

Figure 4 – Commercial production of *Spirulina* using raceway ponds.



Source: Earthrise

As *Spirulina* is a high quality foodstuff, nutrients are added to the growth ponds and CO₂ is bubbled into the water (Earthrise, 2004). This does not help treat sewage, and deliberately adding CO₂ does not help mitigate climate change.

Appendix 2 - Transport Energy Requirements

According to the International Energy Outlook 2008, over the next 25 years, 'world demand for liquids fuels³⁵ and other petroleum is expected to increase more rapidly in the transportation sector than in any other end use sector'.

Region	2005	2010	2015	2020	2025	2030
OECD³⁶	58.5	60.5	63.8	65.6	67.0	68.8
North America	32.2	33.7	35.6	36.8	37.9	39.4
Europe	18.7	19.1	19.8	20.1	20.2	20.3
Asia	7.7	7.8	8.4	8.7	8.9	9.1
Non-OECD	31.7	39.9	46.7	53.1	59.4	66.6
Europe and Eurasia	4.8	5.8	6.6	7.2	7.8	8.5
Asia	13.0	17.3	21.9	26.2	30.4	35.0
Middle East	4.9	5.8	6.2	6.8	7.3	8.0
Africa	3.1	3.7	4.1	4.5	4.9	5.3
Central and South America	5.9	7.2	7.8	8.4	9.0	9.9
Total World	90.2	100.4	110.5	118.7	126.5	135.4

³⁵ Liquid fuels and other petroleum (also referred to as liquids) include petroleum-derived fuels and non-petroleum-derived fuels, such as ethanol and biodiesel, coal-to-liquids, and gas-to-liquids. Petroleum coke, which is a solid, is included. Also included are natural gas liquids, crude oil consumed as a fuel, and liquid hydrogen.

³⁶ Organisation for Economic Co-operation and Development

Appendix 3 – Calculation of algal productivity related to solar energy

A major problem with start-up productivities claimed relate to solar energy conversion with photosynthesis.

US Southwest solar energy=2 MWhr (7.2 GJ)/m²-yr

~assume 90% reaches the crop/or algae in pond

~45% is PAR (photosynthetic active radiation)

~ 90% photons are absorbed by PS pigments

22% max PS efficiency (photons -> biomass energy)

~75% loss to light saturation and photoinhibition

~15% loss to respiration (growth, maintenance)

Calculation (best case, year-round algae culture):

$7.2 \text{ Gigajoules} \times 0.9 \times 0.45 \times 0.9 \times 0.22 \times 0.25 \times 0.85 = 0.12 \text{ Gigajoules}$

= Efficiency ~1.7% and ~20Gigajoules/metric tonne biomass

= ~60 metric tonne/hectare/year @~25% oil=15 metric tonne/hectare/year

~2,000 gallons oil/acre/year (22,467 litres oil/hectare/year) current technology

Maybe 2-3 times this yield with GMO strains or vertical PBRs.

Source: Benemann, J, 5th Annual World Congress on Industrial Biotechnology,

Chicago, April 30, 2008