ALTERNATIVE AVIATION FUEL FEEDSTOCK: THE MICROALGAE SOLUTION?

L. Rye*, D. Batten
Energy Transformed Flagship, CSIRO, Australia
lucasrye@gmail.com

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Abstract

Limited biomass feedstock availability is expected to restrict industry uptake of bio-refined transportation fuel [1]. This work seeks to investigate the potential for heterotrophic microalgae to provide Australia's commercial aircraft fleet with a secure, environmentally sustainable alternative fuel feedstock through lifecycle analysis. High level results demonstrated that, using baseline yield figures available in the literature (Li et al. 12.8 g/L at 48.7% lipids [2]), production of hydroprocessed renewable jet fuel from heterotrophic algae has an inferior greenhouse gas footprint when compared to fossil refined Jet A-1. This is largely due to the electricity consumption during cultivation and the associated footprint from a coal based electricity grid. Optimisation of the cultivation stage – both inputs and algae yield – is expected to significantly improve the sustainability of this pathway; however, the identification of a sustainable (e.g. waste) carbohydrate source remains to be proven.

1 Introduction

Increasing economic and environmental pressures coupled with the inability to diversify to other non-hydrocarbon products has resulted in the aviation sector searching for fully fungible alternative fuels. Recent activity has demonstrated incident free operation – without airframe or engine modification – of blends (50% maximum) refined from biomass feedstock [1, 3]. These test programs supported the recent inclusion of hydroprocessed renewable esters and fatty acids (HRJ) in the jet fuel specification (ASTM D7566; 50% blend), thus allowing the sector to operate commercial biofuel flights. Limited feedstock availability is however, expected to restrict industry uptake of bio-refined jet fuel [1].

Cultivation of microalgae as a second generation feedstock for bio-oil production – which may then be upgraded to jet fuel using hydroprocessing techniques – has gained much interest in recent years with the literature citing high yields, rapid growth rate, marginal land utilisation and sustainable water usage (seawater or wastewater) as some of the key benefits [4]. The vast majority of research and start-up organisations are focusing on cultivation of phototrophic algae for bio-oil production (via photosynthesis using carbon dioxide and light as carbon and energy sources respectively).

Phototropic raceway cultivation, however, provides a low biomass dry weight yield per litre of cultivation medium, with values of 0.3 $gL^{-1}d^{-1}$ (i.e. 20 $gm^{-2}d^{-1}$) frequently cited. Case study analysis has shown that between 5-30% of this may be extracted as bio-oil, thus representing a best case daily yield of 0.015-0.1 g of upgradable bio-oil per litre of cultivation medium harvested. This dilute culture throughput significantly increases processing cost (e.g. harvesting, dewatering and oil extraction) and thus represents a significant economic barrier if the system is designed to produce only low value bio-oil.

Studies reveal that cultivation of heterotrophic microalgae – culture grown in the dark using carbohydrate as both carbon and energy source – could result in higher production of biomass and lipid content in cells [5, 6]. Yan et al. [7] demonstrate this potential, at laboratory scale, by reporting an equivalent bio-oil yield of 8.3 ml per cultivation litre per day. Heterotrophic algae as a source of bio-oil feedstock for jet fuel production thus warrants further investigation in order to establish the economics and sustainability of this pathway.

This work seeks to investigate the potential of heterotrophic microalgae to provide Australia's commercial aviation fleet with a secure, environmentally sustainable alternative fuel feedstock through a preliminary (high level) lifecycle analysis (LCA). LCA involves taking into account both direct and upstream emissions. In the context of aviation, this includes not only the combustion emissions from aircraft (direct emissions) but also those associated with the fuel's extraction, production, transportation, processing, conversion and distribution (upstream emissions). Assessment of the process lifecycle also provides for a preliminary 'back of the envelope' economic evaluation. A brief review of current and future jet fuel demand and other potential alternative fuel pathways is provided.

2 Background

In 2009 Australia consumed approximately 44,000 ML of transportation fuels, of which 6,000 ML was Jet A-1. The continual growth of the aviation sector (5.7% p.a asia-pacific [8]) is expected to place increased pressure on refinery/import infrastructure (Figure 1).

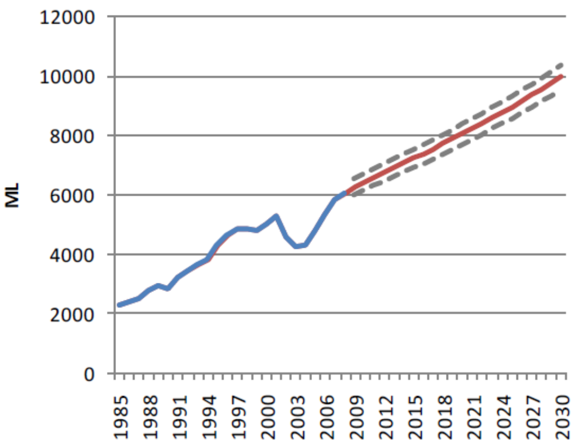

Fig 1. Jet fuel demand [9]

ASTM D7566-11a provides for aviation turbine fuel containing up to 50% synthesised hydrocarbons. Supplying the specification maximum with HRJ therefore requires 3,000 ML of product at 2009 consumption levels. This presents a formidable challenge, requiring large tracks of arable land or 15 times available estimates of collectable waste oils. Importantly, the aviation sector will need to compete with other industries to secure these feedstocks. The arable land required for selected feedstocks (palm, Jatropha, Canola) to independently supply 50% of Australia's transportation fuel demand (e.g. petrol, diesel and Jet A-1) is shown in Figure 2; the 2007 wheat crop area is provided for reference.

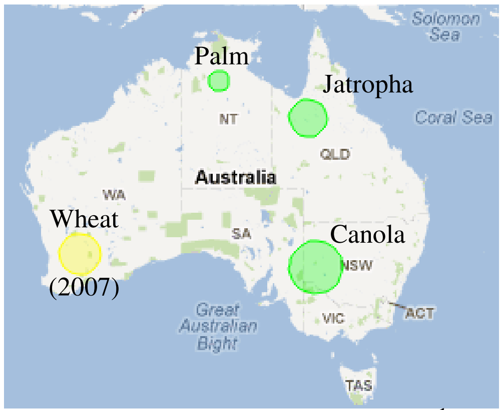

Fig 2. Oil crop land demand[1]

Production of jet fuel from an array of lignocellulosic based pathways (e.g. hydrothermal liquefaction, Fischer Tropsch (BTL), pyrolysis, etc.) reduces feedstock demand by converting the whole plant rather than just the oilseed. However, these technology pathways have not been demonstrated at a commercial scale. The transportation of low carbon dense feedstock over large distances also raises sustainability issues. As outlined in the introductory section, heterotrophic microalgae, a feedstock which has already been demonstrated and approved as a commercial aviation fuel blend (e.g. Solazyme HRJ [10]) may provide a solution. In this work the LCA software package, Simapro v7, is used to assess both the greenhouse gas footprint (GHG) and energy balance (energy returned on energy invested; ERoEI) of aviation fuel derived from 50% heterotrophic microalgae oil.

[1] Palm, Jatropha and Canola are NOT native Australian species.

3 Method

In order to evaluate the lifecycle of microalgae derived jet fuel, both upstream (refinery) and direct (combustion) emissions must be considered. The lack of algae-to-biofuel processes operating at scale coupled with the commercial sensitivities of the sector required the development of a hypothetical production scenario. This scenario was developed and later populated using information from the literature as well as results from engineering correlations. The culture of heterotrophic algae and subsequent processing and conversion into jet fuel blend stock is shown in Figure 3. Importantly, although the data reported in this paper may look precise, they are simply estimates based on the judgment of the authors. There remains significant uncertainty about the viability of the heterotrophic algae-to-biofuels process, as it has not been demonstrated at sufficient scale.

Combustion emission data is available both in the literature (e.g. [11]) and from engine certification testing (e.g. ICAO emissions databank [12]). Importantly, although these data are based on conventional jet fuel, alternative product must be compositionally similar to Jet A-1 in order to satisfy the certification requirements. This has been verified experimentally by Rye [13], who measured variation of gaseous combustion emissions from hydrocarbon controlled fuels. Thus fossil Jet A-1 emission data are used in this analysis, however, a correction is applied to take into account biogenic CO_2 (see Section 3.3).

3.1 Heterotrophic Cultivation

Heterotrophic cultivation of microalgae is assumed to take place using multiple 0.2 ML industrial bioreactors; selected to represent a system of sufficient capacity to supply a 50% blend of HRJ to Australia's aviation sector. Cultivation data is based on pilot scale (750 L bioreactor) experimental work conducted by Li et al. [2]. This work reported a final algae concentration of 12.8 g/L at 48.7% lipids after a 184 h cultivation period. The group has since achieved significantly higher yields (e.g. 70.9 g/L at 57.6% lipid content after 178 h; Yan et al. [7]) at laboratory scale, and although Li et al. reported consistency between lab (5 L), pilot and industry (11 kL) bioreactor yields, the earlier pilot data were used in this work; largely due to data completeness.

Extrapolation of pilot data to the proposed full scale bioreactor was based on maintaining an equivalent aggregator tip speed, and is one of the many scale-up techniques used in industry (see [14]). Scale-up introduces obvious uncertainty, however, the selection of low yield data provides for the assessment of a baseline production target. For simplicity, only cultivation carbon (e.g. sugar; assumed to be sourced from Australian sugarcane[2]) is included in this analysis. The bioreactor operating conditions – scaled up from Li et al's [2] work – are shown in Table 1.

Once the culture reaches sufficient volume (after 184 hours), it is transferred for harvesting, oil extraction and subsequent upgrading using hydroprocessing techniques.

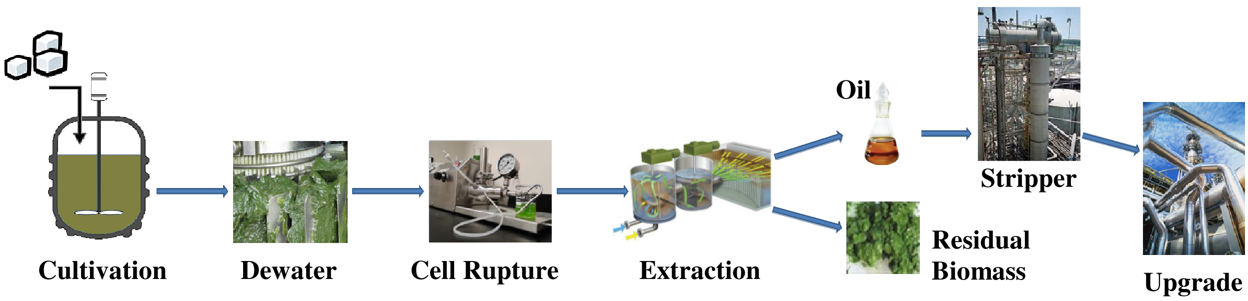

Fig. 3 Heterotrophic microalgae process diagram

[2] Use of edible sugar is considered unsustainable. Use of lignocellulosic sugars will be required for industry scale-up.

Table 1. Bioreactor culture model (per 0.20 ML reactor batch)

Parameter	Value	Unit	Comments
Inputs			
Sugar	6,810	kg	Each unit of algae requires 2.66 units of sugar
Water	0.193	ML	Culture water
Steam	1,912	MJ	Bioreactor sterilisation
Heat	10,506	MJ	Culture thermal control
Water pump	8	kWh	Bioreactor fill electricity demand
Sparger	11,578	kWh	Blower electricity demand
Impeller	10,385	kWh	Electricity demand (equivalent RPM tip speed)
Outputs			
Culture	0.20	ML	Microalgae concentration: 12.8 g/L

Table 2. Process inputs (per 0.20 ML reactor batch)

Parameter	Value	Unit	Notes
Inputs			
Centrifuge	240	kWh	Dewatering electricity (evodos.eu)
Homogenizer	174	kWh	Cell rupture electricity (niro-soavi.com)
Mixer settler	24.3	kWh	Oil extraction electricity
Stripper	1,245	MJ	Solvent recovery heat (natural gas)
Hexane	241	kg	Make-up hexane required
Outputs			
Oil	1,066	kg	Recovered crude microalgae lipids
Biomass	1,366	kg	Recovered biomass

3.2 Processing

Harvesting/dewatering is assumed to take place using a centrifuge. This stage removes 30% of the cultivation water. The small size of the algae cells coupled with the presence of a cell wall requires the rupture of the microalgae cells prior to oil extraction. This is assumed to be achieved using an industrial homogenizer. Samarasinghe et al. [15] demonstrated high-pressure homogenizer to be an effective technique to rupture *Nannochloris oculata* cell walls. The lysed cell solution is then mixed with solvent in a mixer settler to extract the lipids. A stripper is used to recover the hexane solvent from the lipid-solvent solution, producing a crude algae lipid which may subsequently be upgraded into a transportation fuel. The residual biomass stream may be processed further for energy or sugar recovery; the effects of which are discussed in Section 4. The process requirements to produce crude algae lipids, as shown in Figure 3, are summarised in Table 2.

For this analysis, the crude algae lipids are assumed to be upgraded into renewable jet fuel using petrochemical hydroprocessing techniques. This process removes oxygen, nitrogen and other heteroatoms, producing HRJ. HRJ contains no aromatics and thus the product must be blended with Jet A-1 (50% maximum concentration) to satisfy certification requirements. Input data for the hydroprocessing requirement in this analysis has been adapted from Stratton et al. [16].

3.3 Combustion Emissions

In order to evaluate the total lifecycle footprint of algae refined HRJ, the combustion emissions must also be considered. Under carbon accounting practices, CO_2 emitted during the combustion of a biofuel – entitled biogenic CO_2 – is assumed to be equal to that which was absorbed during photosynthetic growth. Heterotrophic algae, however, does not absorb atmospheric CO_2. Nevertheless, the cultivation of sugarcane, for the purposes of a carbon feedstock, absorbs atmospheric CO_2. Therefore the associated combustion emissions are considered biogenic.

Combustion however, also produces other gaseous (i.e. CO, CH_4, NOx, etc) and particulate matter (volatile and non-volatile organics) emissions that must be considered when evaluating the biofuels lifecycle. Total emissions are therefore accounted through a CO_2 equivalent (CO_2e) value based on their global warming potential as defined in the Kyoto Protocol. A breakdown of selected exhaust data is shown in Table 3; adapted from the CSIRO Simapro database. Importantly, as the specification limits HRJ blend percentages to 50%, emissions of fossil based Jet A-1 must also be considered.

Table 3. Jet A-1 and 50:50 Jet-HRJ direct emissions (per MJ)

Emission	Jet A-1	50:50 Jet-HRJ	Units
CO_2 (fossil)	69.0	34.5	g CO_2
CO_2 (bio)	0.0	34.5	g CO_2
CO	0.078	0.078	g CO
NOx	0.26	0.26	g NOx
PM10	15.5	15.5	mg PM_{10}

4 Results and Discussion

Combining the upstream (culture and processing stages; Section 3.1-2) and direct (combustion; Section 3.3) emissions provides the total greenhouse gas impact and energy intensity of the heterotrophic microalgae production system (Table 4). Emissions data are reported per MJ of product produced (e.g. g CO_2e/MJ) from the batch cultivation system, with the energy intensity representing the ratio of energy output over input (e.g. ERoEI; MJ/MJ). The lifecycle impact of Jet A-1 is included for comparison.

The results show that production of jet fuel using heterotrophic algae has an inferior greenhouse gas footprint compared with fossil refined Jet A-1. Considering neat HRJ, total upstream emissions are 529 g CO_2e/MJ. This is due almost entirely to the upstream impact of the cultivation stage; specifically the impeller (223 g CO2e/MJ) and air sparging motor (249 g CO2e/MJ) electricity demand from a mostly fossil based grid (coal). A breakdown of emissions contributing to 3.5% or more of the total impact is shown in Figure 4. The cumulative emissions impact is represented by the thermometer bars shown on each process block.

Table 4. Jet A-1 and 50:50 Jet-HRJ emissions (g CO_2e per MJ) and ERoEI

Process	Jet A-1	50:50 Jet:HRJ	Units
Upstream	15.2	272.2	g CO_2e
Direct	69.9	35.4	g CO_2e
Lifecycle	85.1	307.7	g CO_2e
Energy in	57.0	185.5	MJ/kg
Energy out	43.2	43.8	MJ/kg
ERoEI	0.76	0.24	MJ/MJ

Importantly, it should be realised that the bioreactor impeller and sparging energy requirements have been extrapolated using a constant tip speed and sparging air to cultivation medium ratio, respectively. Significant uncertainty surrounds these values. The result however, highlights the importance of optimising the culture conditions at scale. Considering the operating expense (OpEX) requirement for just the impeller and sparging air, the cost of electricity is $AU 1.45/L of HRJ produced. At current Jet A-1 prices ($US 0.72/L; June 15th 2012 [17]), the process is clearly uneconomical if the production of HRJ is the only goal.

The high cost of fixed cultivation inputs – e.g. the impeller and sparger operating electricity demand is relatively independent of culture yield – ensures that both the lifecycle footprint and the process economics are sensitive to culture yield. For example, if Yan et al. [7] laboratory yield values are replicated at scale, the impact of the impeller and sparger is reduced to 34 and 38 g CO_2e/MJ respectively. Clearly the optimisation of growth conditions at scale is critical to the success of this pathway. Use of residual biomass may also improve the process economics through the generation of an additional income stream (e.g. stock feed sales) or reduce OpEX through energy or material recovery. Energy recovery through anaerobic digestion is not a new idea (e.g. [18]), however, incorporating this process into the scenario reduces total upstream emissions from 529 to 501 g CO_2e/MJ. Alternatively, it may be possible to extract the starch (carbohydrates) from the residual microalgae biomass and, using enzymes, convert the biomass into a carbon feedstock for subsequent culture batches.

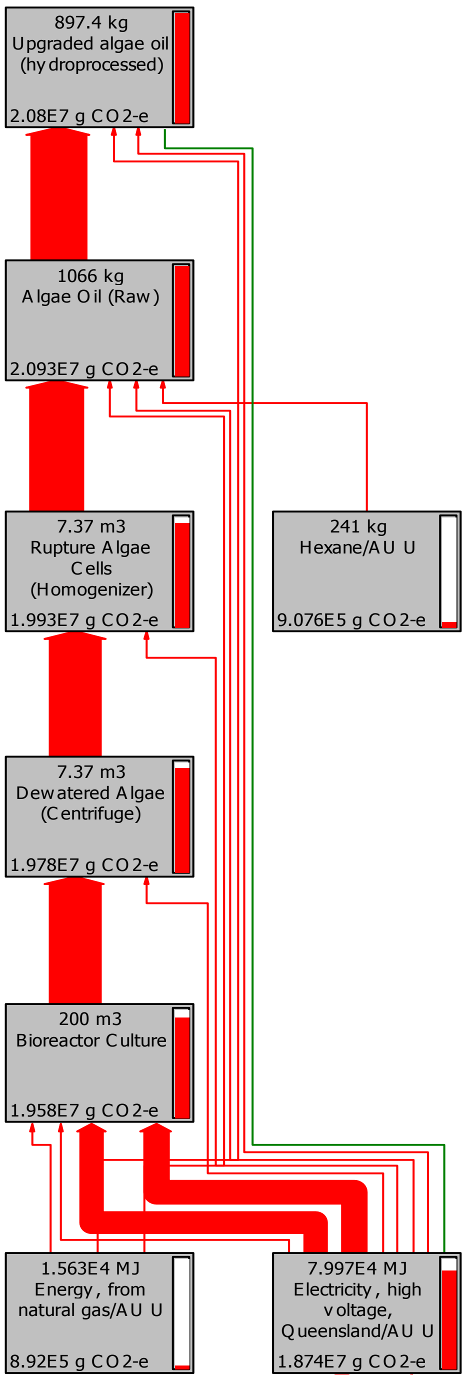

Figure 4. 100% HRJ LCA impact

Identifying a sustainable sugar source (and/or improving sugar recovery) will become a critical issue for process scale-up. Cultivation of sufficient sugarcane to support the required scale-up of heterotrophic algae (e.g. 3000 ML) requires 1.6 million ha of land. This is more than three times the land required for the cultivation of palm oil (0.5 million ha); which in itself avoids the need for high CapEX expenditure (e.g. multiple 0.2 ML bioreactors). Identification of a lignocellulosic feedstock, as well as a suitable process to convert this feed into carbohydrates suitable for heterotrophic growth, will be critical in both the economic and sustainable scale-up of this technology.

5 Conclusion

The scenario analysis, modelled on baseline literature yield data, has demonstrated that cultivation of heterotrophic microalgae for the production of Jet A-1 blend stock is both uneconomic and inferior in terms of greenhouse gas emissions and energy usage when compared to Jet A-1. The analysis identified that improvement in cultivation conditions, in particularly the bioreactor energy inputs and algae yield, will be critical in developing a sustainable production system. The literature reports that the required yields are close to being demonstrated in the laboratory; however, even if the laboratory yields translate to an industrial scale, the identification of a suitable sugar source is critical. Especially as the cultivation of sugarcane for heterotrophic microalgae requires more land than simply growing palm oil.

To date, the authors are not aware of any commercial operation producing HRJ on cost comparison with Jet A-1. Therefore, although this work has focused on limited cultivation stage costs, further research is required to improve both upstream and downstream process economic understanding.

References

[1] L. Rye, S. Blakey, and C. W. Wilson. "Sustainability of supply or the planet: a review of potential drop-in alternative aviation fuels," *Energy & Environmental Science,* vol. 3, pp. 17-27, 2010.

[2] X. Li, H. Xu, and Q. Wu. "Large-scale biodiesel production from microalga Chlorella protothecoides through heterotrophic cultivation in bioreactors," *Biotechnology and Bioengineering,* vol. 98, pp. 764-771, 2007.

[3] S. Blakey, L. Rye, and C. W. Wilson. "Aviation gas turbine alternative fuels: A review," *Proceedings of the Combustion Institute,* vol. 33, pp. 2863-2885, 2011.

[4] C. Posten and G. Schaub. "Microalgae and terrestrial biomass as source for fuels—A process view," *Journal of Biotechnology,* vol. 142, pp. 64-69, 2009.

[5] L. Brennan and P. Owende. "Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 557-577, 2010.

[6] Y. Liang, N. Sarkany, and Y. Cui. "Biomass and lipid productivities of <i>Chlorella vulgaris under autotrophic, heterotrophic and mixotrophic growth conditions," *Biotechnology Letters,* vol. 31, pp. 1043-1049, 2009.

[7] D. Yan, Y. Lu, Y.-F. Chen, and Q. Wu. "Waste molasses alone displaces glucose-based medium for microalgal fermentation towards cost-saving biodiesel production," *Bioresource Technology,* vol. 102, pp. 6487-6493, 2011.

[8] Airbus. "Delivering the Future (pocket guide), Global Market Forecast 2011-2030," 2011.

[9] A. Smart, Y. Chou, K. Willett, and A. Hodby. "Petroleum import infrastructure in Australia," ACIL Tasman 2009.

[10] E. Goossens. "United Agrees To Buy Algae Biofuel From Solazyme For Air Travel," in *Bloomberg*, ed, 2011.

[11] J.E.Penner, D.H.Lister, D.J.Griggs, D.J.Dokken, and M.McFarland. "Aviation and the Global Atmosphere," ed: IPCC, 1999.

[12] ICAO. International Civil Aviation Organization Aircraft Engine Emissions DataBank [Online]. Available: http://easa.europa.eu/environment/edb/aircraft-engine-emissions.php

[13] L. Rye. "The Influence of Alternative Fuel Composition on Gas Turbine Combustion Performance," Department of Mechanical Engineering, University of Sheffield, 2012.

[14] F. A. Holland and F. S. Chapman. *Liquid Mixing and Processing in Stirred Tanks*. New York: Reinhold Publishing, 1966.

[15] N. Samarasinghe, S. Fernando, R. Lacey, and W. B. Faulkner. "Algal cell rupture using high pressure homogenization as a prelude to oil extraction," *Renewable Energy,* vol. 48, pp. 300-308, 2012.

[16] R. W. Stratton, H. M. Wong, and J. I. Hileman. "Quantifying Variability in Life Cycle Greenhouse Gas Inventories of Alternative Middle Distillate Transportation Fuels," *Environmental Science & Technology,* vol. 45, pp. 4637-4644, 2011/05/15 2011.

[17] IATA. (2012, 15th June). *Jet Fuel Price Monitor*. Available: http://www.iata.org/whatwedo/economics/fuel_monitor/Pages/index.aspx

[18] W. J. Oswald and C. G. Golueke. "Biological Transformation of Solar Energy," in *Advances in Applied Microbiology*. vol. Volume 2, W. U. Wayne, Ed., ed: Academic Press, 1960, pp. 223-262.

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