Downstream Processing of Marine Microalgae for the Commercial Scale Production of Biofuels

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Abstract

Several species of microalgae have lipid yields that are about 4 to 5 times of that from the highest oil bearing terrestrial plants such as oil palm. Furthermore, marine species can offer the additional advantage of not competing with farm produce for fresh water or arable land. These advantages make marine microalgae appear to be attractive as a feedstock for the production of biofuels; however, despite intensive research, the production cost of microalgal biomass remains high at about A$ 10 kg^{-1}. In comparison, plantation oil such as canola can be available of about $1 L^{-1} and this large cost difference makes algal biofuels uncompetitive. Hence, the sustainability of microalgal biofuel production depends very much on the technical, energetic and economic issues involved with production.

Microalgal lipids and carbohydrates are major feedstock for renewable fuels and the downstream processing can broadly be classified into four steps: harvesting, dewatering, cell disruption and extraction of the desirable products. The specific objectives for the PhD study were harvesting and cell disruption of microalgae; these objectives were structured towards the development of pilot scale production of marine microalgae and included technical, energetic and economic evaluations. Below are details for these objectives:

I. Harvesting: the objective was to increase the biomass concentration from about 0.2 kg m^{-3} to about 20 kg m^{-3}. Such level of concentration would be suitable for the next unit of processing such as cell disruption or secondary dewatering. Flocculation (electro- and microbial-) were applied as the harvesting methods with induced mechanical mixing and electrode separation as the novelties in

energy optimization techniques. The scope of this study included the technical investigation and development of these harvesting methods, evaluation of their energy requirements, plant designs and economic analyses; all these areas were deemed to be necessary for the determination of the viability of such processes.

II. Cell disruption: disruption processes with potential for the commercial scale biofuel production were investigated with emphasis on the process reliability, energy requirement and disruption efficiencies. The novelty was the determination of disruption energy efficiencies by comparing the process energy input with the theoretically derived values of cell disruption.

III. Cell mechanics: mechanical cell wall properties that affect the disruption process were investigated. Atomic force microscopy was used to evaluate the disruption energy requirements and determine the efficiencies of various cell disruption processes. The novelty was the measurement of disruption energy requirement for individual cells. From the experimental value obtained, the specific disruption energy on a per kg basis was calculated to determine the energy efficiencies of various disruption methods.

It was found that the mixing of microalgal media during electroflocculation is essential for the reduction in electrical energy requirement, and hydraulic baffles can provide an energy efficient technique for such purpose. The energy required for such mixing is 3.2 kJ kg^{-1} of the equivalent dry mass based on the design criteria that the value of Camp number is between 10^4 to 10^5 and the velocity gradient is between 100 s^{-1} to 10 s^{-1}. The cost for harvesting by microbial flocculation, including energy, raw material and capital depreciation, was estimated to be A$ 0.26 kg^{-1} of the equivalent dry mass. On the other hand, the cost of harvesting by electroflocculation, including electrical energy, aluminium dissolution and capital depreciation, was estimated to be \$ 0.185 kg^{-1} of the equivalent dry biomass. The energy consumptions by both types of flocculation have the potential to be further optimised.

For the extraction of lipids for the production of biodiesel, mechanical cell disruption methods are preferred due to the lower risk of contamination of products and the ease of scale up. The drawback is that current mechanical disruption processes have high specific energy consumption that is in excess of that can be available from the combustion of the entire cell mass. The disruption energy may be optimized by selecting processes that are relatively energy efficient and the combination of cell disruption with solvent extraction.

The disruption energy as measured by the use of Atomic Force Microscopy revealed that an average value of 17.4 pJ was required for the disruption of an individual *Tetraselmis sp.* cell, this value is equivalent to specific disruption energy of 673 J kg^{-1} of dry microalgal biomass. In comparison, disruption by hydrodynamic cavitation, one of the most energy efficient technique, requires specific disruption energy input of 33 MJ kg^{-1} of the dry biomass. This large difference indicates the low efficiency in the mechanical cell disruption and more innovation is required for the sustainability of such processes in the production of biofuels.

This thesis advances the knowledge in the harvesting and cell disruption of microalgae from the laboratory to pilot scale. In the area of harvesting, advances were made in the scale up on the plant design, energy optimisation and economics of microbial- and electro-flocculation; while in the area of cell disruption, advances were achieved on the understanding of the energy requirements for large scale mechanical cell disruption processes, and the fundamental cell mechanics with respect to disruption. All these work has been presented as journal publications as detailed in the Preface of this thesis.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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I would firstly like to thank my supervisors, A/Prof Peter Ashman and A/Prof David Lewis for the encouragement and support throughout the years of research. The many hours of discussion, guidance and support are invaluable in the completion of this thesis and the publication of various journal papers.

I would also like to thank Prof Michael Borowitzka from Murdoch University, Western Australia, for his overall co-ordination of the APP Project; Dr Steven Pahl, research fellow from the School of Chemical Engineering, University of Adelaide, for technical assistance with microalgae culturing; Mr. Jason Peake and Mr. Jeffrey Hiorns, workshop technicians, for advice and construction of various experimental rigs; Mrs. Mary Barrow and Mrs. Sue Earle from the School office for everything from stationery to morning tea; and finally all my colleagues for all their help and support.

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Preface

This thesis is submitted as a portfolio of publications according to the "Specifications for Thesis 2012" of the University of Adelaide. The journals, in which the papers were published, have high impact factors in the research field of Chemical Engineering. Data on the impact factors of the journals are listed below:

Journal Title	Impact Factors	
	2 year	5 year
Chemical Engineering Research and Design	1.96	2.03
Biomass and Bioenergy	3.64	4.62
Bioresource Technology	4.98	5.35
Applied Energy	5.11	4.45

The main body of work contained in this thesis is within the following four journal papers:

1. **Lee, A.K.,** Lewis, D.M., Ashman, P.J. 2010. Energy requirements and economic analysis of a full-scale microbial flocculation system for microalgal harvesting. *Chemical Engineering Research and Design*, 88, (8), 988-996.

2. **Lee, A.K.,** Lewis, D.M., Ashman, P.J. 2012. Disruption of microalgal cells for the extraction of lipids for biofuels: Processes and specific energy requirements. *Biomass and Bioenergy*, 46, 89-101.

3. **Lee, A.K.,** Lewis, D.M., Ashman, P.J. 2013. Force and energy requirement for microalgal cell disruption: An atomic force microscope evaluation. *Bioresource Technology*, 128, (0), 199-206.

4. **Lee, A.K.,** Lewis, D.M., Ashman, P.J., 2013. Harvesting of marine microalgae by electroflocculation: The energetics, plant design, and economics. Applied Energy, 108, (0), 45-53.

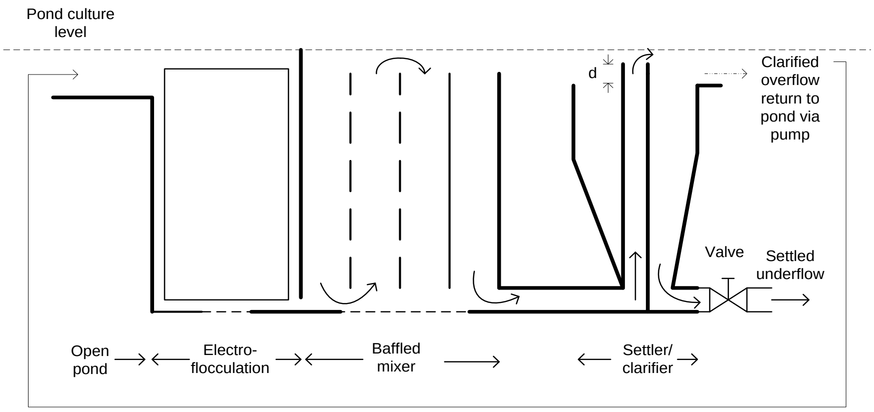
Below are additional publications that are relevant to the present work and included in the appendices of this thesis:

Lee, A.K., Lewis, D.M., Ashman, P.J. 2009. Microbial flocculation, a potentially low-cost harvesting technique for marine microalgae for the production of biodiesel. *Journal of Applied Phycology*, 21(5), 559-567.

Andrew K Lee, David M Lewis, Peter J Ashman, 2010. An assessment of large scale microalgal harvesting methods for the production of biodiesel. Proceeding from CHEMECA 2010, Hilton, Adelaide, SA, Australia.

Pahl, S., **Lee, AK.,** Kalaitzidis, T., Ashman, P., Sathe, S., & Lewis, D. (2013). Harvesting, Thickening and Dewatering Microalgae Biomass. In M. A. Borowitzka & N. R. Moheimani (Eds.), *Algae for Biofuels and Energy* (Vol. 5, pp. 165-185): Springer Netherlands.

Errata

Page	Line	Erratum
3.5	Column 1, Paragraph 2, Line 2	Replace “$m^2 s^{-1}$” by “Pa s”
6.8	Section 2.2.2	Replace ”air” by “gas”
6.9	Section 3.2	Additional note: “Cell disruption processes such as high pressure homogenizer, bead mill or hydrodynamic cavitation require high shear and impact for the disruption. Algal concentrate with dry mass over 3 % has a consistency of thick cream and will require a significant amount of energy to attain the high velocity necessary to generate such shear”.
6.10	Section 3.3.3	Additional figure and note:  The design of the pilot plant is based on the laboratory batch test results. The flocculation time is expected to be of similar value due to the high turbulence (Eq 11 shows high Reynolds number, hence adequate mixing). The required settling distance, d, as indicated in the figure, should also be similar to the experimental settling value.
6.11	Table 5	Additional note: “Lang factors were not mentioned in the cited literatures in Table 5; hence, such factors have not been used here to compare all these cost estimations on a similar basis,.”