CHEMICAL ENGINEERING TRANSACTIONS

VOL. 50, 2016

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Katharina Kohse-Höinghaus, Eliseo Ranzi

ISBN 978-88-95608-41-9; **ISSN** 2283-9216

DOI: 10.3303/CET1650071

Life Cycle Assessment of Technologies for Greenhouse Gas Emissions Reduction in Sugarcane Biorefineries

Mateus F. Chagas [a,b], Otávio Cavalett [a], Bruno C. Klein [a,b], Rubens Maciel Filho[a,b], Antonio Bonomi [a,b]

[a]Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE), Centro Nacional de Pesquisa em Energia e Materiais (CNPEM), Caixa Postal 6192, CEP 13083-970, Campinas, São Paulo, Brasil
[b]Faculdade de Engenharia Química (FEQ), Universidade Estadual de Campinas (Unicamp). CEP 13083-852, Campinas, São Paulo, Brasil.
mateus.chagas@bioetanol.org.br

Since sugarcane biorefineries are a large source of CO_2 emissions, there is an opportunity of using or capturing this pollutant. An alternative would be to use mechanisms to capture, transport and inject CO_2 into underground geological formations with the purpose of permanent storage of this gas, the so called Carbon Capture and Storage or CCS. Another possibility is to produce biodiesel from microalgae cultivated with CO_2 to replace fossil diesel used in the sugarcane production chain. Environmental impacts using life cycle assessment of both technologies, CCS and biodiesel production from microalgae, integrated into first and second generation ethanol production plants were assessed. Biodiesel production from microalgae promoted reduction in all the assessed environmental impact categories, decreasing about 35 % of climate change impacts. CCS presented the highest climate change reduction transforming ethanol in a net carbon absorber. However, higher environmental impact in other categories are observed in this case.

1. Introduction

One of the critical issues regarding biofuels production is the emissions of greenhouse gases (GHG) throughout their lifecycles. Despite the fact that ethanol produced from sugarcane in Brazil has been recognized as an advanced biofuel, it is necessary to search for technological alternatives to ensure even smaller life cycle GHG emissions. Since sugarcane processing plants present large CO_2 emission (fermentation and combustion of biomass to attend plant power demand), there is a great potential for using or capturing this gas rather than releasing it into the atmosphere.

An alternative to reduce GHG emissions associated with ethanol production process would be to use mechanisms to capture, transport and inject CO_2 into underground geological formations with the purpose of permanent storage of this gas. Carbon Capture and Storage (CCS) applied to ethanol production plants may transform this process into a net carbon absorber, since CO_2 emissions in the biorefinery largely exceed the amount of GHG emissions of ethanol production life cycle.

Another possible alternative is to use the CO_2 to increase the products portfolio of the sugarcane biorefinery by growing microalgae for the production of biodiesel (replacing fossil diesel in the agricultural and transport operations of sugarcane production stage) and coproducts.

Even though there are no large-scale plants using these technologies, they are identified with great potential for reducing environmental impacts of biofuels. This study evaluates these two technological alternatives coupled to first and second generation sugarcane biorefineries, and their effects on the environmental impacts of ethanol.

2. Methods

The Virtual Sugarcane Biorefinery (VSB) is a computer simulation platform developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE/CNPEM) (Bonomi et al., 2016). This tool was used to

Please cite this article as: Chagas M., Cavalett O., Klein B., Maciel Filho R., Bonomi A., 2016, Life cycle assessment of technologies for greenhouse gas emissions reduction in sugarcane biorefineries, Chemical Engineering Transactions, 50, 421-426 DOI: 10.3303/CET1650071

evaluate the integration of both technologies, CCS and biodiesel production from microalgae, into first and second generation sugarcane biorefineries. Assessment of the agricultural stage of sugarcane production was carried out using the CanaSoft model (Bonomi et al., 2016). Sugarcane production system considers mechanized operations for planting, harvesting and recovery of 50% of the straw from the field using bales (Cardoso et al., 2013; Chagas et al., 2016). Aspen Plus® was used to simulate industrial processes, obtaining mass and energy balances for each evaluated scenario. Environmental impacts were assessed using Life Cycle Assessment methodology, aided by software SimaPro®. CML 2 Baseline 2000 v2.05 was selected as life cycle impact assessment method. Datasets for upstream processes are taken from ecoinvent 2.2 database, modified by Chagas et al. (2012). Environmental impacts are allocated between ethanol and coproducts based on the participation of each product on revenues (economic allocation).

2.1 Baseline scenarios for first and second generation

An optimized first generation (1G) plant producing ethanol and surplus electricity (autonomous distillery), as described by Dias et al. (2014), was considered in this study. This plant produces ethanol from sugarcane juice (sucrose and reducing sugars) and operates only during the sugarcane harvesting period, which is around 200 days per year. Optimized features, such as straw recovery, reduced steam consumption, efficient high-pressure boilers and molecular sieves for ethanol dehydration process, allow large electricity surplus. This 1G process configuration is depicted in Figure 1.

In the integrated 1G2G scenario, part of the lignocellulosic material (bagasse and straw) is sent to the 2G process. 2G process operates year-round (330 days) using lignocellulosic material stored during sugarcane season. The process starts with a steam explosion pretreatment followed by a separate hydrolysis and fermentation process. Pentoses (C5) liquor from pretreatment is fermented using a genetically modified microorganism, while glucose (C6) liquor from enzymatic hydrolysis is fermented along with 1G juice using conventional yeasts. Residual solids are burnt in the cogeneration unit. Process parameters for 2G process consider long term prospects as described by Milanez et al. (2015). A proposed block flow diagram for the 2G process integrated to the 1G autonomous distillery is presented in Figure 1.

2.2 Carbon Capture and Storage

Only the highly concentrated CO_2 stream generated during ethanol fermentation was considered to be used for CCS, as presented in Figure 1. Using CO_2 also from cogeneration is also a possibility, but it would require additional downstream processes for purification and conditioning. In proposed CCS systems, CO_2 is transported from its source to a storage site through a pipeline and is then injected into the reservoir through an injection well, usually after compression. Parameters used to simulate this alternative integrated to 1G and 1G2G scenarios are presented in Table 1.

Energy required to compress CO_2 for transportation and injection in the well were calculated using Aspen Plus®. This energy requirement as well as the material of the pipeline construction (carbon steel, 25 years lifespan) are considered in the life cycle inventories for the CCS scenarios.

According to Goraieb et al. (2005), there are several geological formations in the state of São Paulo that could be used for CO_2 storage. An initial estimate for transportation distances between the biorefinery and injection wells was assumed as 200 km. A sensitivity analysis on the results considering 1000 km was also performed.

Table 1: Summary of technical parameters for CCS scenarios

Parameter	Value	Unit	Reference
Inlet pipeline pressure	9.6	MPa	IPCC (2005)
Injection pressure	15.0	MPa	IPCC (2005), Goraieb et al (2005)
Pipeline diameter (CCS coupled to 1G plant)	10	in	Calculated based on CO_2 flow rates
Pipeline diameter (CCS coupled to 1G2G plant)	14	in	Calculated based on CO_2 flow rates
Transport distance	200	km	Goraieb et al (2005)

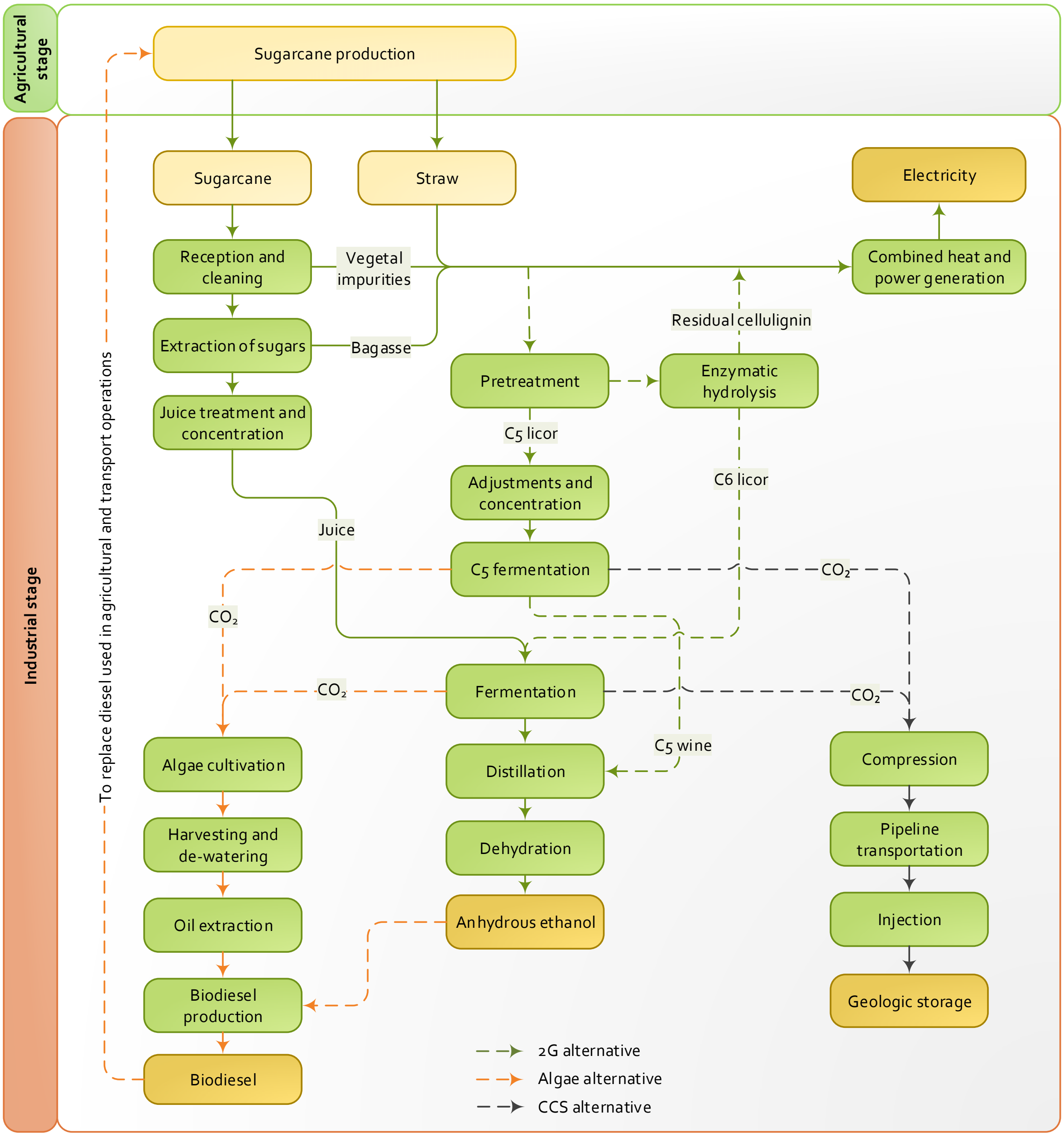

Figure 1: Block flow diagram for integrated Algae and CCS scenarios in 1G and 1G2G biorefineries

2.3 Biodiesel production from microalgae scenarios

Although high CO_2 purity is not required for algae culture, scenarios of biodiesel production from microalgae use only the CO_2 stream generated during ethanol fermentation in order to be compatible with CCS scenarios, as depicted in Figure 1.

Several species of algae have been tested under different operational and environmental conditions. A wide variety of parameters for algae growing process is presented in literature, e.g. growth rate, oil content, ability to remove CO_2 from different sources and with different concentrations. A summary of main parameters used to simulate biodiesel production from algae is presented in Table 2.

All the CO_2 from fermentation is considered to be used in the algae cultivation process. However, it would be necessary to store part of the CO_2 to operate only during daylight period. A sensitivity analysis is presented considering that only 50% of CO_2 from fermentation is used for algae production and the other 50% is released to the atmosphere during the night.

For the biodiesel production from algae oil, an homogeneous alkaline transesterification using ethanol was considered. Part of the biodiesel produced by this scenario is used to replace the fossil diesel used in the agricultural operations of sugarcane production and transportation to the industrial plant. Biodiesel surplus is considered to be sold at the market as well as the other coproducts: algae meal and glycerine.

Table 2: Summary of technical parameters for algae and biodiesel production scenarios

Parameter	Value	Unit	Reference
Process parameters			
Algae productivity	25	$g\ m^{-2}\ d^{-1}$	Quinn et al. (2014)
Algae oil content	45.7	%	Collet et al (2014)
CO_2 required for algae	1.8	$kg_{CO2}\ kg_{algae}^{-1}$	Olialgae (2015)
CO_2 uptake	80.00	%	Olialgae (2015)
Extraction efficiency	85.5	%	Quinn et al. (2014)
Biodiesel conversion	98	%	Cheng (2009)
Inputs			
Urea	18	$g\ kg_{algae}^{-1}$	Quinn et al. (2014)
Diammonium phosphate	27	$g\ kg_{algae}^{-1}$	Quinn et al. (2014)
Coagulant	10	$g\ kg_{algae}^{-1}$	Quinn et al. (2014)
Hexane	5.3	$g\ kg_{oil}^{-1}$	Quinn et al. (2014)
Ethanol	159	$g\ kg_{biodiesel}^{-1}$	Del Vecchio (2006)
Sodium hydroxide	0.8	$g\ kg_{biodiesel}^{-1}$	Del Vecchio (2006)
Hydrochloric acid	8.0	$g\ kg_{biodiesel}^{-1}$	Del Vecchio (2006)
Potassium hydroxide	5.5	$g\ kg_{biodiesel}^{-1}$	Del Vecchio (2006)
Energy consumption			
Algae cultivation	38	$kWh\ ha^{-1}\ d^{-1}$	Quinn et al. (2014)
Algae harvesting and oil extraction	0.018	$kWh\ kg_{algae}^{-1}$	Quinn et al. (2014)
Biodiesel production	25	$kWh\ t_{biodiesel}^{-1}$	Del Vecchio (2006)

3. Results and discussion

The key technical results for the evaluated scenarios are shown in Table 3. It can be noticed that integrated 1G2G process increases ethanol production by 46 %, but reduces electricity output by about 67 %. However, production of larger amount of liquid biofuel presents positive environmental results, as it can be seen in the comparative life cycle impacts presented in Table 4 and Figure 2. When integrating the 2G process into the biorefinery, the GHG emissions per unit of energy of ethanol are reduced by 20 %, with lower environmental impacts in all the evaluated categories.

Table 3: Outputs in the biorefinery scenarios per metric tonne of processed sugarcane stalks

Product	Unit	1G			1G2G		
		Base	Algae	CCS	Base	Algae	CCS
Anhydrous ethanol	L	85.4	85.4	85.4	124.8	124.8	124.8
Electricity	kWh	185.8	180.5	172.9	61.6	54.6	43.6
Biodiesel [a]	L	-	9.4	-	-	15.3	-
Glycerin (88%)	kg	-	1.3	-	-	1.9	-
Microalgae meal (37% protein)	kg	-	18.0	-	-	26.4	-

[a] Refers to the surplus biodiesel only; biodiesel used to replace fossil diesel in the agricultural operations is already accounted for.

Biorefinery scenarios coupled with biodiesel production from algae slightly reduce surplus electricity due to energy requirements for microalgae cultivation, harvesting and oil extraction and conversion to biodiesel. This reduction is more evident in 1G2G integrated scenarios, due to the large amount of CO_2 used in the process, since more ethanol is produced by C6 and C5 fermentation. Reduction in climate change impacts of ethanol production reaches 35 % for both 1G algae and 1G2G algae scenarios when compared to respective Baseline scenarios. This reduction is mainly due to fossil diesel replacement in the sugarcane production phase. Even higher reduction is observed in the abiotic depletion, since fossil oil used for diesel production has an important contribution in this environmental impact. Lower reduction observed in other assessed categories are due to nutrients used for microalgae cultivation.

A sensitivity analysis considering that only 50% of CO_2 from fermentation is used obviously leads to a lower reduction in GHG emissions. About 30% lower climate change impacts for both 1G algae and 1G2G algae scenarios compared to respective Baseline scenarios.

CCS scenarios show the best results for climate change impacts. Biorefineries with CCS have the ability to make ethanol production process a net carbon absorber since the captured and stored CO_2 largely exceeds the GHG emitted from the entire ethanol production life cycle. Applying this technology, emissions fall from 20 to -8.8 g CO_2 eq per MJ of ethanol in 1G process, and from 16.1 to -17.5 g CO_2 eq per MJ of ethanol in integrated 1G2G process. These reductions could be even higher if CO_2 from flue gases is included in the analysis. Reduction in surplus electricity and pipeline construction inputs slightly increases ethanol impacts in all the other considered environmental impact categories, as shown in Figure 2.

A sensitivity analysis considering longer distances (1000 km) for CO_2 transportation with recompression units every 200 km shows that CCS coupled with 1G would result in climate change impacts of -7.8 g CO_2 eq/MJ, and, coupled with 1G2G, to -17.0 g CO_2 eq/MJ. It indicates that even for large transport distances CCS could present very interesting results in terms of climate change impacts.

Table 4: Greenhouse gas emissions for ethanol produced in the evaluated scenarios (g CO_2 eq/$MJ_{ethanol}$)

Life cycle emissions	1G			1G2G		
	Base	Algae	CCS	Base	Algae	CCS
Sugarcane and straw production	16.8	10.0	17.0	13.4	7.6	13.6
Process emissions	2.3	1.9	2.3	1.1	0.8	1.1
1G and 2G inputs	0.9	0.7	0.9	1.6	1.1	1.6
Microalgae and biodiesel inputs	-	0.9	-	-	1.0	-
CCS infrastructure	-	-	0.2	-	-	0.1
CO_2 captured and stored	-	-	-29.2	-	-	-33.9
Final score	20.0	13.5	-8.8	16.1	10.5	-17.2

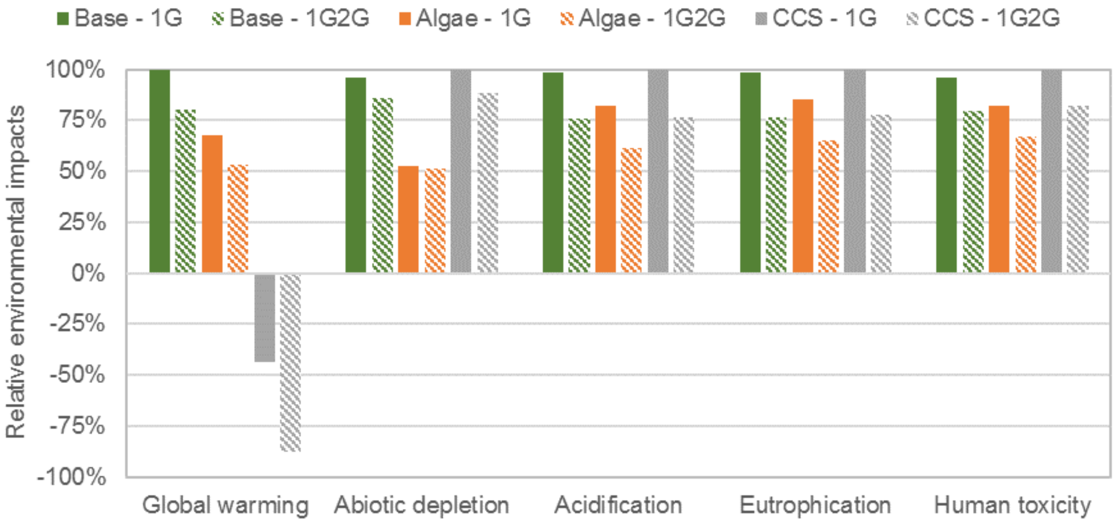

Figure 2: Relative environmental impacts for evaluated scenarios

4. Conclusions

Both technologies – CCS and biodiesel production from microalgae – integrated into 1G and 1G2G ethanol autonomous plants were assessed in this study. Biodiesel production from microalgae promoted reductions in all the assessed environmental impact categories, decreasing greenhouse gases (GHG) emissions in about 35 % when compared to baseline scenarios. CCS presented the highest potential of reducing GHG emissions, transforming the ethanol production process into a net carbon absorber. However, negative consequences in other environmental impact categories are observed. Despite the promising environmental performance, these technologies have to prove to be economically sustainable to be applied in large scale. Further economic analysis will help to better understanding sustainability of these biorefinery scenarios.

Acknowledgments

The authors would like to thank Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP (contract grant number 2010/17139-3) for financial support.

Reference

Bonomi A., Cavalett O., Cunha M.P, Lima, M.A.P., 2016, Virtual Biorefinery: An Optimization Strategy for Renewable Carbon Valorization. Springer International Publishing, Switzerland, 2016. DOI: 10.1007/978-3-319-26045-7

Cardoso T.F., Cavalett O., Chagas M.F., Morais, E.R., Carvalho J.L.N., Franco H.C.J., Galdos M.V., Scarpare F.V., Braunbeck O.A., Cortez L.A.B., Bonomi A., 2013, Technical and economic assessment of trash recovery in the sugarcane bioenergy production system. Sci. Agric., 70, DOI: 10.1590/S0103-90162013000500010

Chagas M.F., Bordonal R.O., Cavalett, O., Carvalho, J.L.N, Bonomi A., La Scala Jr N., 2016, Environmental and economic impacts of different sugarcane production systems in the ethanol biorefinery. iofuels, Bioproducts & Biorefining (in press). DOI: 10.1002/bbb.1623

Chagas, M.F., Cavalett, O., Silva, C.R.U., Seabra, J.E.A., Bonomi, A., 2012, Adaptação de Inventários de Ciclo de Vida da cadeia produtiva do etanol de cana-de-açúcar no Brasil. In: III Congresso Brasileiro em Gestão do Ciclo de Vida de Produtos e Serviços, Maringá, Brazil, 2012.

Cheng J., Ed., 2009, Biomass to Renewable Energy Processes. CRC Press, Boca Raton, Florida.

Collet P., Lardon L., Hélias A., Bricout S., Lombaert-Valot I., Perrier B., Lépine O., Steyer J.P., Bernard O., 2014, Biodiesel from microalgae – Life cycle assessment and recommendations for potential improvements, Renewable Energy, 71, 525-53, DOI: 10.1016/j.renene.2014.06.009

Dias M.O.S., Cavalett O., Maciel Filho R., Bonomi A., 2014, Integrated First and Second Generation Ethanol Production from Sugarcane. Chemical Engineering Transactions, 37, 445-450, DOI: 10.3303/CET1437075

Del Vecchio E., 2006, Presentation: Biodiesel investments workshop (in Portughese). BNDES, Rio de Janeiro, Brazil. < http://goo.gl/SCJdMF> accessed 09.11.2015

Goraieb C.L, Iyomasa W.S., Appi C.J., Eds., 2005, Subterranean storage of natural gas: Technology to support the growth of the natural gas sector in Brazil. IPT, São Paulo, Brazil (in Portughese).

IPCC, Intergovernmental Panel on Climate Change, 2005, Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, 2005. ISBN-13 978-0-521-86643-9

Milanez A.Y, Nyko D., Valente M.S., Sousa L.C., Bonomi A., Jesus C.D.F., Watanabe M.D.B., Chagas M.F., Rezende M.C.A.F., Cavalett O., Junqueira T.L., Gouveia V.L.R., 2015, De promessa a realidade: como o etanol celulósico pode revolucionar a indústria da cana-de-açúcar - uma avaliação do potencial competitivo e sugestões de política pública. BNDES Setorial , 41, 237-294.

Oilgae, 2015. Capture of CO_2 Emissions Using Algae: A Research Document by Oilgae < http://goo.gl/jKaywK> accessed 20.11.2015

Quinn J.C, Smith T.G, Downes, C.M., Quinn C., 2014, Microalgae to biofuels lifecycle assessment – Multiple pathway evaluation, Algal Research, 4, 116-122, DOI: 10.1016/j.algal.2013.11.002