Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 143 (2017) 767–773

Energy
Procedia

www.elsevier.com/locate/procedia

World Engineers Summit – Applied Energy Symposium & Forum: Low Carbon Cities & Urban Energy Joint Conference, WES-CUE 2017, 19–21 July 2017, Singapore

Decentralized algal energy system design at various urban densities and scales

Steven Jige Quan[a b], Thomas K. Igou[d], Soowon Chang[c], Florina Dutt[b], Daniel Castro-Lacouture[c], Yongsheng Chen[d], Perry Pei-Ju Yang[b]*

[a]Graduate School of Environmental Studies, Seoul National University, Seoul, 151-742, South Korea
[b]School of City and Regional Planning, Georgia Institute of Technology, Atlanta, GA 30332, USA
[c]School of Building Construction, Georgia Institute of Technology, Atlanta, GA 30332, USA
[d]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Abstract

Algal biotechnology seems promising to be implemented as a decentralized urban energy system due to its high biomass productivity and its utilization of urban waste streams. Current literature on algal energy systems mainly focuses on algal strain, reactor, and process improvements, neglecting the systems level consequences arising when algal biotechnology is integrated into the urban system as a part of renewable energy resources. The overall performance of the integrated system can vary due to different availability levels of urban nutrient, solar and CO_2 resources, and the cost can vary due to different settings of material transports and processing. This study explores two critical questions: How does the urban density affect overall system performance? At what spatial scale could the optimal system performance be achieved? The study investigates these questions through test cases in real urban settings in Atlanta, Georgia, USA. Four neighborhoods are selected with different building densities representing the urban core, urban, suburban and rural areas, with scales of 0.5, 1, and 2 km radiuses as the system boundaries. Decentralized algae energy system design is proposed for each site, while available vacant lands are identified to place such energy systems. Based on relevant literature and validated seasonal cultivation data from the Algae Testbed Public-Private-Partnership (ATP^3) project, as well as established data and methods for urban resource availability assessment and transport calculations, the overall energy performance of the decentralized system is estimated. The results show that higher density leads to higher energy performance while scale has no obvious effects on the energy performance. At the same time, the negative net energy production suggests that under current algal technologies, it is still far from feasible to implement the system in real urban settings.

Peer-review under responsibility of the scientific committee of the World Engineers Summit – Applied Energy Symposium & Forum: Low Carbon Cities & Urban Energy Joint Conference.

Keywords: Algal cultivation, Dencentrailzied urban energy system, Energy performance, Density, Scale

---

Peer-review under responsibility of the scientific committee of the World Engineers Summit – Applied Energy Symposium & Forum: Low Carbon Cities & Urban Energy Joint Conference.
10.1016/j.egypro.2017.12.760

1. Introduction

Our cities have been paid more and more attention in addressing the global challenges of resource depletion and climate change, as they are consuming more energy and generating more waste. In the pursuit of solutions, algal biotechnology shows potential to be implemented as a decentralized urban energy system due to its high biomass productivity and its utilization of urban waste streams. A typical algae cultivation system requires water, carbon, sunlight and nutrients (primarily nitrogen and phosphorous), which are already contained in the urban waste stream and could be utilized after appropriate treatment [1]. The biological process normally generates biomass, oxygen and water, which is treated for nutrient removal. There are three types of algae cultivation systems used in experiments and industrial applications: open raceway ponds (ORP), photobioreactors (PBR) and hybrid systems. Among them, the ORP system is one of the oldest and most studied systems for the mass culture of algae.

Although in recent years, the algal system has been a focus in the bioenergy field, current literature mainly focuses on algal strain, reactor, and process improvements [2-6], neglecting the systems level consequences arising when algal biotechnology is integrated into the urban system as a component of renewable energy resources. Demonstrative projects in cities such as the algae-powered building in Germany [7] and the freeway algae garden in Switzerland [8] displayed the great potential of this technology to be implemented in the urban environment. However, their system boundaries are very confined and performances were not well examined. To better evaluate the potential of algal biotechnology as a decentralized urban energy system, a more comprehensive approach needs to be taken to examine the overall performance of the system which can vary due to different availabilities of urban nutrient, solar and carbon dioxide resources, and the cost variation created by different settings of material transports and processing.

Two critical properties emerge in the integration of the algae engineered system with the urban spatial and societal system: system boundary and resource density, which jointly determine the size and performance of integrated systems. This paper aims to explore their influence on the design of integrated systems: How does the urban density affect overall system performance? At what spatial scale could the optimal system performance be achieved?

To answer those questions, this research proposes a design of integrated urban-algal systems as shown in Fig. 1 and applies the design to real neighborhood contexts in Atlanta, GA with different density and scale properties to compare the performances. This paper focuses on the energy performance which includes the input energy for systems to function and energy production, but also considers other environmental impacts in the performance evaluation.

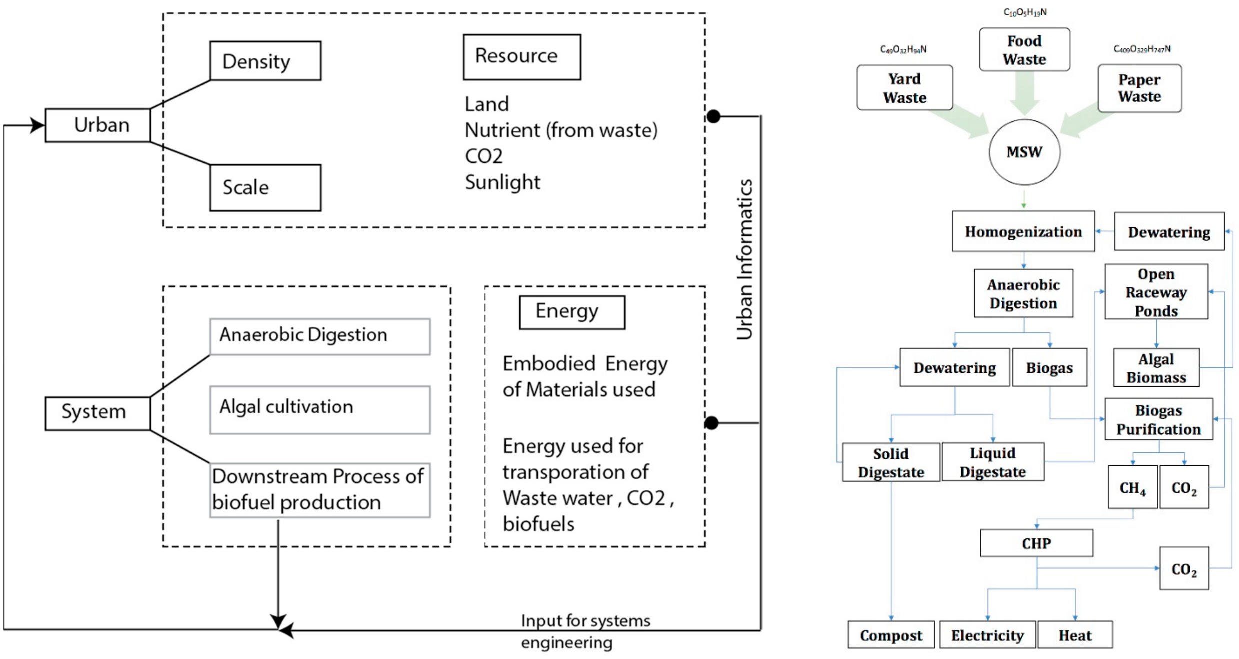

Fig. 1. Overall design of the integrated urban-algal system (left); Specific design of the algal subsystem (right).

2. Methodology

2.1. Neighborhood case selection and data collection

Four different types of neighborhoods in Atlanta are selected to initialize the urban context investigation. Differences in the types of the neighborhoods selected are based on urban densities and scales to represent the urban environment in downtown, urban, peri-urban and rural areas. To study the effect of the scale, at each chosen density, concentric circles of fixed radiuses of 0.5 km, 1 km and 2 km are selected. Three concentric circular zones are considered with the neighborhood centroid as the center to allow for a uniform density distribution. As such 12 sites were studied in this research with 4 types of density mixtures. The selected neighborhoods and cases as well as their basic parameters are shown in Fig. 2 and Table. 1.

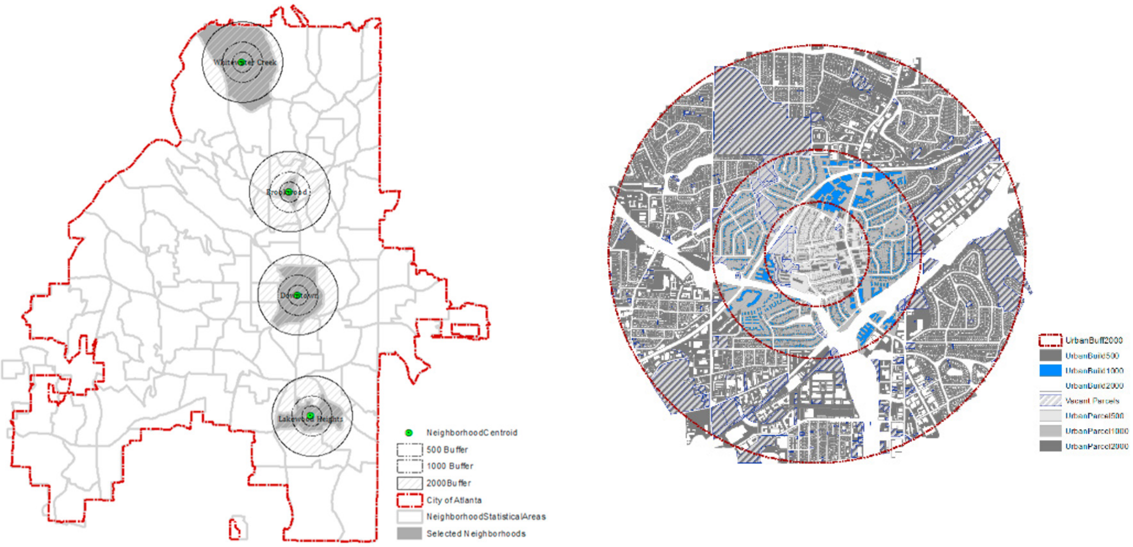

Fig. 2. Selection of 12 cases in 4 neighborhoods in Atlanta, US (left); Urban environment elements such as parcels and buildings in Brookwood urban neighborhood at the scale of 0.5 km, 1 km and 2 km radius (right).

Table 1. Cases in typical Atlanta neighborhoods and building density

Neighborhood	Case with 0.5 km radius	Case with 1 km radius	Case with 2 km radius
Downtown (Atlanta Downtown)	5.32	4.40	1.82
Urban (Brookwood)	0.61	0.55	0.49
Peri- urban (Whitewater Creek)	0.07	0.10	0.12
Rural (Lakewood Heights)	0.10	0.13	0.13

The spatial and societal data are collected from governmental websites and USGS website for the 12 case areas, including tax parcel data, building footprint data, Landsat DEM (Digital Elevation Model) raster datasets and street network data. The datasets are organized and cleaned to a great extent on the platform of GIS.

2.2. System type selection and data collection

An algal engineered system is designed to turn urban waste into energy (Fig.1 right). Such systems should include three main parts: pre-cultivation processing to turn waste into macronutrients (N, P) for algal utilization, algae cultivation, and post-cultivation processing to turn algae culture into energy. In the pre-cultivation processing, anaerobic digestion is used to convert urban waste into nutrient-rich effluent. In the algae cultivation process, the open raceway pond is adopted in the system due to its ease in implementation in the existing urban area with available sunlight resource, etc. In the post-cultivation processing, different from other studies using oil extraction technologies, this study still uses the anaerobic digester to generate biogas and further produce electricity and heat, in order to reduce the investment of the entire system.

The details of the ORP system including the system size and performance were gathered from testbed data during a period of two and a half years at Georgia Institute of Technology in Atlanta, GA within the Algae Testbed Public-Private-Partnership (ATP^3) Network [9]. ATP^3 was established through a $15M grant from the US Department of Energy (DoE) for collaborative algae production research and commercialization. The system uses nutrients, light, water, and CO_2 as the inputs for production which is also influenced by the water temperature. While the nutrients, water and CO_2 have been controlled in the experiments, the sunlight and the air temperature which determines the water temperature vary greatly for the outdoor experiment site. In order to understand how these inputs and environmental variables influence algal production, an algal productivity model was established by statistical analysis to predict algae biomass production with those variables, based on the experiment results and the hyperlocal data obtained at the field site.

The other systems including the anaerobic digester are designed using the most popular systems. The details of the systems including efficiency and energy requirements are based on technical reports and literature [10-14].

2.3. Estimation of system inputs in the neighborhood cases

The integrated urban-algal system requires inputs from the urban area including the nutrients in urban waste and sunlight availability. Also its productivity is influenced by the urban air temperature. In neighborhoods with different building floor areas, urban forms and tree covers, those variables can differ greatly: the urban waste volume is determined by the population and building floor areas, the sunlight availability is affected by the shading effect, and the air temperature is influenced by the Urban Heat Island (UHI) effect. This study uses different methods and modeling tools to estimate and simulate those variables for each case with different densities and scales.

For the nutrients in urban waste, the study uses the occupancy-based accounting method to estimate the volume of Municipal Solid Waste (MSW). It uses the building density and building functions to calculate the occupancy capacities of all types of building, and multiplies them by the occupancy schedules and the MSW generation ratio provided by national and city-wide surveys [15-17]. The MSW contains nutrient-rich organic wastes of food, paper and yard clippings with the percentage of 12.9%, 38.7% and 10.50% respectively [17, 18]. The overall N and P contents are then calculated as 2.6 g/kg and 11.7g/kg respectively based on the proportions of those types and the composition of the nutrients in each type [19]. The methods are applied to the test cases to get the MSW and nutrient quantities (Fig. 3).

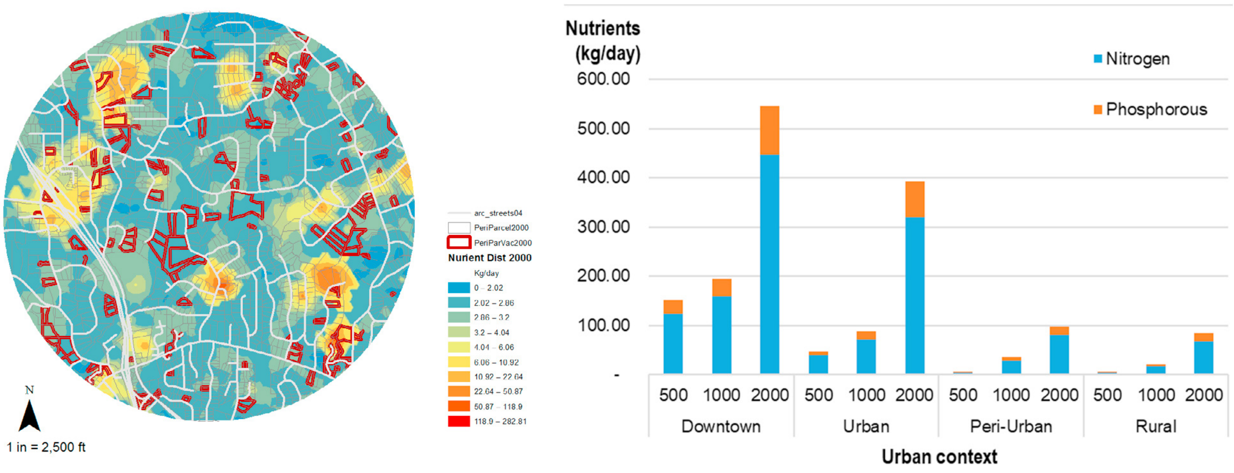

Fig. 3. The potential MSW mapping in the peri-urban neighborhood (left); Potential P and N quantities in the cases (right).

For solar availability, the Solar Analyst Tool in ArcGIS is used to estimate the daily average solar irradiance for all vacant parcels in the cases which can be potential pond sites. For the air temperature, the UWG/Radiance engine is used to simulate the UHI effect and the average daily air temperatures are estimated for all the cases.

2.4. System sizing and siting

The integrated urban-algal decentralized system requires certain spaces and locations for operation. The systems are sized based on the potential nutrient quantities and the available vacant parcels as input and spatial constraints. In the three parts of the systems, the pre-cultivation processing and the post-cultivation processing can be placed together as a centralized system on one parcel while the ponds for algal cultivation can be distributed on different parcels. To determine the sites of the systems, network analysis is used to determine the optimal siting scenario given the spatial relations of the vacant parcels and their solar irradiances influencing transport cost and productivity (Fig. 4).

Fig. 4. Siting of the urban-algal systems in the peri-urban neighborhood with the scale of 2 km (left), 1 km (middle) and 0.5 km (right)

2.5. Performance calculation

With the nutrient, solar irradiance and air temperature data, the algal model developed based on the ATP^3 field experiments, the efficiency of each subsystem in the urban-algal system, and the transport distance for nutrient and water supplies, the overall energy performance of the system is estimated for each case including both the energy production incurred by algal cultivation as well as energy costs for waste and water transport and system operation.

3. Results

The analysis results are shown in Table 2. Different from the general optimistic results in the literatures [2-6, 18, 20], with all the energy consumption for system operation considered, the energy performance of the system defined as net energy production per MSW quantity is negative, which means overall the system costs energy instead of providing net biofuels. It shows that under the current algal and related technologies, it is difficult to make the system feasible for implementation with high productivity.

Comparisons among different cases show that higher density leads to higher net energy production generally, while scale seems to have no obvious relation with the energy performance of the decentralized urban-algal system (Fig. 5). The density influence is due to the resource density and its tight relation to building density, which determines the productivity of the entire system. For the relation between energy and scale, as scale increases, the positive effect on energy production due to increased system efficiency for larger sizing is offset by the increasing energy cost with longer distances required for transportation of urban waste and pond water which leads to no obvious relation.

Table 2. Energy performance of the decentralized system in the 12 cases

Neighborhood	Downtown			Urban			Peri- urban			Rural		
Scale (radius in km)	0.5	1	2	0.5	1	2	0.5	1	2	0.5	1	2
Waste-Energy Balance (GJ per ton MSW)	-0.16	-0.39	-0.72	-0.65	-1.12	-3.25	-23.12	-4.32	-4.08	-13.14	-21.57	-26.41
Energy Saving ($ per ton MSW)	-2.65	-6.68	-12.16	-11.09	-19.07	-55.31	-392.97	-73.38	-69.39	-223.37	-366.75	-448.91
Percentage of Energy used for water pumping	79%	79%	79%	79%	79%	90%	96%	91%	91%	95%	96%	96%

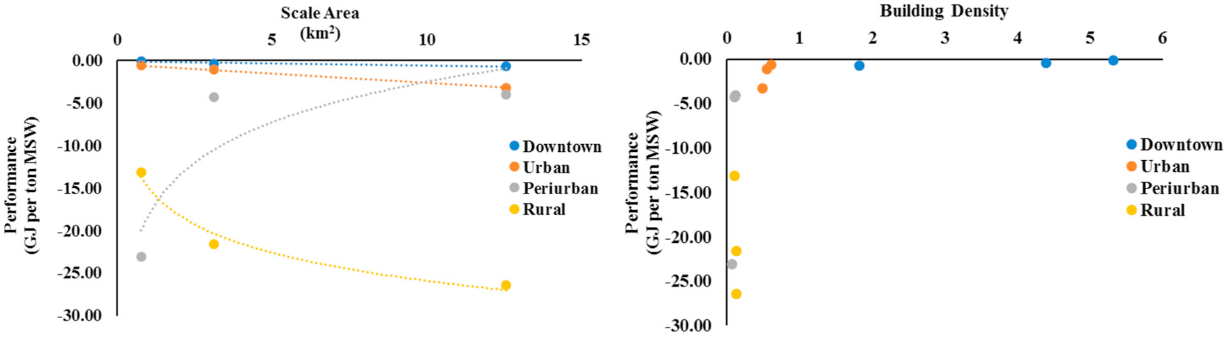

Fig. 5. Relation between energy performance and: scale (left); density (right).

4. Conclusions and discussions

This study examines the overall performance of the decentralized urban-algal system situated in real urban environments to understand how density and scale of urban areas influence the system energy performance. The study proposes the design of the decentralized system in 12 case areas in Atlanta, GA, USA that represent downtown, urban, peri-urban and rural environments. The preliminary results indicate that higher density leads to higher energy performance while the scale doesn't show obvious correlation to energy performance. But in contrast to results in literature, when all the energy costs for the system operation are considered, in all cases the system could not provide positive net energy production.

The results suggest that under current algal technology design scenarios, it is still far from feasible to implement the system in real urban settings. Further scrutiny of energy balance of the system showed that energy for water pumping is the major source of energy use in the system, accounting for between 79% and 96% of total energy demand. This calls for further study on how to reduce water usage in algae production. A simple scenario estimation shows that if the water usage can be reduced by 70%, the system begins to provide net positive energy in downtown and urban neighborhoods. At the same time, the evaluation of such systems should include not only energy production, but also the reuse of urban waste and educational impacts. The system design and implementation should consider broader impacts. The team is currently working on the LCA (Life Cycle Assessment) of the urban-algal system to examine the energy and cost performance from a LCA perspective and the further cleaning of GIS data from local government entities to improve accuracy.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No.1230961.

References

[1] J.K. Pittman, A.P. Dean, O. Osundeko, The potential of sustainable algal biofuel production using wastewater resources, Bioresource technology, 102 (2011) 17-25.

[2] B. Singh, A. Guldhe, I. Rawat, F. Bux, Towards a sustainable approach for development of biodiesel from plant and microalgae, Renewable and sustainable Energy reviews, 29 (2014) 216-245.

[3] Y.P. Cai, G.H. Huang, Q. Tan, L. Liu, An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part II. Case study, Renew Sust Energ Rev, 15 (2011) 3051-3073.

[4] Y. Chisti, Biodiesel from microalgae, Biotechnology advances, 25 (2007) 294-306.

[5] I. Rawat, R.R. Kumar, T. Mutanda, F. Bux, Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production, Appl Energ, 88 (2011) 3411-3424.

[6] E. Ehimen, Z. Sun, C. Carrington, E. Birch, J. Eaton-Rye, Anaerobic digestion of microalgae residues resulting from the biodiesel production process, Appl Energ, 88 (2011) 3454-3463.

[7] KOS Wulff Immobilien GmbH, BIQ Das Algenhaus, in, 2012.

[8] Planet Editor, Switzerland Installs Algae Farm Over Highway to Suck Up Carbon Emissions, in, 2014.

[9] Algae Testbed Public Private Partnership (ATP3), ATP3 Unified Field Study Data, in, 2017.

[10] S.K. Prajapati, P. Kumar, A. Malik, V.K. Vijay, Bioconversion of algae to methane and subsequent utilization of digestate for algae cultivation: a closed loop bioenergy generation process, Bioresource technology, 158 (2014) 174-180.

[11] H.-W. Yen, D.E. Brune, Anaerobic co-digestion of algal sludge and waste paper to produce methane, Bioresource technology, 98 (2007) 130-134.

[12] J. Ferrer, R. Pretel, F. Durán, J. Giménez, A. Robles, M. Ruano, J. Serralta, J. Ribes, A. Seco, Design methodology for submerged anaerobic membrane bioreactors (AnMBR): A case study, Separation and Purification Technology, 141 (2015) 378-386.

[13] C. Chen, W. Guo, H.H. Ngo, D.-J. Lee, K.-L. Tung, P. Jin, J. Wang, Y. Wu, Challenges in biogas production from anaerobic membrane bioreactors, Renew Energ, 98 (2016) 120-134.

[14] O. Kujawski, H. Steinmetz, Anaerobic Digestion Model based on Mass Balances. Development, Implementation and Validation.

[15] Autodesk, Occupancy Schedules, in, 2017.

[16] P. Beigl, S. Lebersorger, S. Salhofer, Modelling municipal solid waste generation: A review, Waste management, 28 (2008) 200-214.

[17] Georgia Department of Community Affairs, FY 2011 Solid Waste Annual Report, in, Georgia Department of Community Affairs,, 2011.

[18] R. Beck, Georgia Statewide Waste Characterization Study, in, Georgia Department of Community Affairs, 2005.

[19] D. Sullivan, A. Bary, D. Thomas, S. Fransen, C. Cogger, Food waste compost effects on fertilizer nitrogen efficiency, available nitrogen, and tall fescue yield, Soil Science Society of America Journal, 66 (2002) 154-161.

[20] B. Sialve, N. Bernet, O. Bernard, Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable, Biotechnology advances, 27 (2009) 409-416.