CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

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

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863029

Techno-economic Assessment of an Integrated Algae-based Biorefinery with Palm Oil Mill

Nur Nabila Abdul Hamid, Jeng Shiun Lim*

Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
jslim@cheme.utm.my

Palm oil production has become a major contributor to the economy of several tropical countries where palm oil trees can be grown commercially, particularly due to its high productivity and capability to yield more oil from less land area. Palm oil milling activities generate wastewater that is highly polluted and requires to be treated before it can be discharged into the environment. The wastewater generated from the milling activities is defined as palm oil mill effluent (POME). Studies have shown that algae can be grown using wastewater. The utilisation of algae for POME treatment coupled with biogas facilities in the palm oil mill can simultaneously remediate the wastewater and reduce the cost for nutrient and freshwater supplies required for algae growth. This paper investigates the techno-economic potentials of an integrated algae-based bio-refinery with palm oil mill. The proposed superstructure for the integrated bio-refinery includes carbon sequestration, algae growth with wastewater integration from biogas effluent, algae harvesting and dewatering, algal oil extraction, algal oil upgrading, and residual algae processing. Based on the techno-economic analysis conducted, the results show that the processing pathway which consists of open pond, flocculation with alum and centrifugation, drying, solvent extraction with hexane/isopropanol, base catalysed transesterification of algal oil, and combustion of residual algae produces the highest profit of 7.73 x 10^5 USD/y.

1. Introduction

Biomass, which is a renewable source for biofuels production, has been regarded as a promising substitute for fossil fuel due to its potential for carbon mitigation and large scale production (Daoutidis et al., 2013). Algal biomass has been receiving attention in the recent decades to be utilised as feedstock for biorefinery and offers significant advantages over conventional biomass since it has the capability to be used for wastewater bioremediation and carbon sequestration, has high area productivity, and can be grown on non-arable land (Brennan and Owende, 2010).

To gain insights on the economic performance of algae as biorefinery feedstock, systematic methodology can be applied to evaluate the sustainable design of algae processing network. Gupta et al. (2014) developed mixed integer linear programming (MILP) model to maximise the economic potentials of an algae biorefinery. The authors proposed the utilisation of five (5) different types of culture medium, which are waste medium from goat, pig, cow, grass cutter, and poultry chicken to evaluate the growth data for algae as an input to the optimisation model. Rizwan et al. (2015) formulated mixed integer non-linear programming (MINLP) models to determine the optimal biorefinery configurations by maximising two different scenarios - the yield of biofuels and gross operating margin of the system.

Since algae can be used for carbon sequestration and grown using wastewater, algae-based biorefinery can be integrated with different process or industry to enhance the environmental benefits and reduce the cost required for nutrients supply. Several researches have been conducted to investigate the potentials of integrating algae-based biorefinery with another process or industry. Gutiérrez-Arriaga et al. (2014) investigated the potentials of integrating steam power plant with algae-based biorefinery, where CO_2 and electricity are supplied by the power plant. The authors formulated linear programming (LP) model based on genetic algorithm to simultaneously optimise the economic and environmental aspects of the system.

Please cite this article as: Nur Nabila Abdul Hamid, Jeng Shiun Lim, 2018, Techno-economic assessment of an integration of algae-based biorefinery with palm oil mill, Chemical Engineering Transactions, 63, 169-174 DOI:10.3303/CET1863029

Hernández-Calderón et al. (2016) reported the economic advantages of utilising flue gas from industrial power plants as the carbon source to cultivate algae, where MINLP model was formulated to maximise the economic potentials of the system.

Malaysia is the second largest palm oil producer in the world (Malaysian Palm Oil Board (MPOB), 2017) and produces CO_2 and palm oil mill effluent (POME) as waste products. According to Malaysia's Economic Transformation Programme (ETP) in the palm oil and rubber sector, biogas facilities are targeted to be developed at palm oil mills by 2020 (Performance Management & Delivery Unit (PEMANDU), 2013) to treat POME while producing electricity as product. Hultberg et al. (2017), on the other hand, reported that algae can be cultivated using the effluent from biogas process. The aim of this study is to investigate the techno-economic assessment of an integrated algae-based biorefinery with palm oil mill using biogas effluent and waste CO_2 for algae cultivation. A matrix of different technologies is evaluated and the cost for each processing network is then compared.

2. Design of case study

2.1 Integrated algae-based biorefinery with palm oil mill

A case study was designed to investigate the techno-economic potentials of an integrated algae-based biorefinery with palm oil mill. A superstructure of the integrated processes was developed to display the variation of technological alternatives and configuration of the biorefinery network. The techno-economic assessment of the integrated biorefinery is analysed based on the illustrated superstructure. The superstructure of the integration of algae-based biorefinery with palm oil mill is displayed in Figure 1.

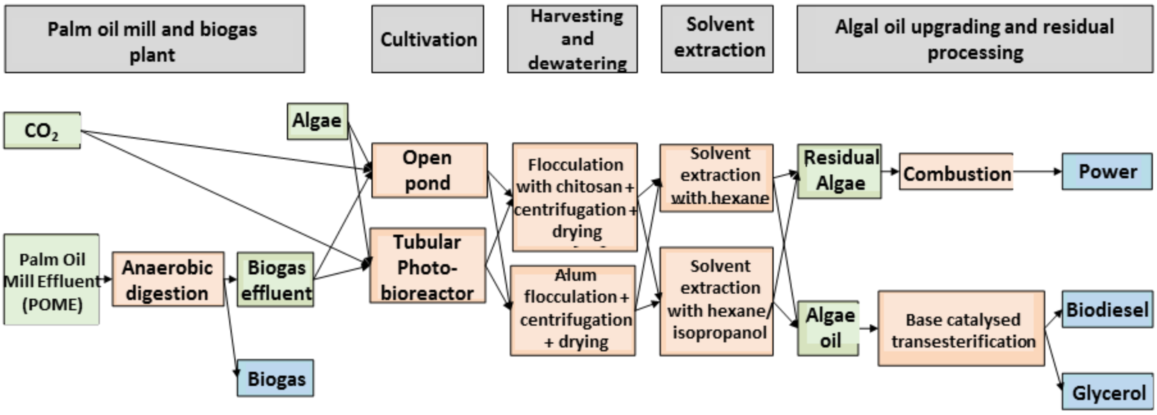

Figure 1: Proposed processing network of an integrated algae-based biorefinery with palm oil mill

According to the proposed chain design (Figure 1), the processing network involve five (5) major stages, which are algae cultivation, algae harvesting and dewatering, algal oil extraction, algal oil upgrading, and residual algae processing. Palm oil mill is integrated with algae-based biorefinery during the initial processing phase of the biorefinery, which is algae cultivation. Waste CO_2 emitted by the mill is supplied into the biorefinery to provide carbon for photosynthesis of algae. POME from the palm oil mill is treated using anaerobic digestion process and the effluent from the digester process is utilised by the biorefinery to supply the water and nutrients (phosphorus and nitrogen) required for algae growth.

2.2 Chain design alternatives

Based on the superstructure illustrated in Figure 1, eight (8) alternative integrated algae-based biorefinery processing chains are evaluated to investigate and compare the potential economic benefits. The complete case processing matrix is summarised in Table 1. The economic analysis on two (2) different type of technologies for cultivation, harvesting and dewatering, and oil extraction processing is conducted to determine the techno-economic feasibility of the processing chain.

Table 1: Summary of processing chain design alternatives

Chain	Processing pathway
1	Open pond – Flocculation with chitosan + centrifugation – Drying – Solvent extraction with hexane – Base catalysed transesterification of algal oil – Combustion of residual algae
2	Tubular photobioreactor – Flocculation with chitosan + centrifugation – Drying – Solvent extraction with hexane – Base catalysed transesterification of algal oil – Combustion of residual algae
3	Open pond – Alum flocculation + centrifugation – Drying – Solvent extraction with hexane – Base catalysed transesterification of algal oil – Combustion of residual algae
4	Tubular photobioreactor – Alum flocculation + centrifugation – Drying – Solvent extraction with hexane – Base catalysed transesterification of algal oil – Combustion of residual algae
5	Open pond – Flocculation with chitosan + centrifugation – Drying – Solvent extraction with hexane/isopropanol – Base catalysed transesterification of algal oil – Combustion of residual algae
6	Tubular photobioreactor – Flocculation with chitosan + centrifugation – Drying – Solvent extraction with hexane/isopropanol – Base catalysed transesterification of algal oil – Combustion of residual algae
7	Open pond – Alum flocculation + centrifugation – Drying – Solvent extraction with hexane/isopropanol – Base catalysed transesterification of algal oil – Combustion of residual algae
8	Tubular photobioreactor – Alum flocculation + centrifugation – Drying – Solvent extraction with hexane/isopropanol – Base catalysed transesterification of algal oil – Combustion of residual algae

2.3 Integrated system characteristics and assumptions

Palm oil mill produces CO_2 and POME as wastes, which can be then utilised by algae-based biorefinery and biogas facility for algae growth. The production of algal biomass in the biorefinery is determined based on the amount of POME released from palm oil mill. The palm oil mill data is based on Sebrang Mill, Sabah, Malaysia and biogas plant data is based on biogas plant from Sumatera, Indonesia (Firdaus et al., 2017). Table 2 summarises the production of CO_2 and POME from palm oil mill and biogas effluent from biogas plant for algae cultivation and Table 3 lists the characteristics of algae (Nannochloropsis sp.).
The assumptions made to evaluate the techno-economic aspects of the system are as follows:

1. CO_2 from palm oil mill and biogas effluent from anaerobic digestion process can be directly used for algae cultivation without prior pre-treatment.
2. Algae productivity and lipid yield when grown in biogas effluent are the same as when grown in conventional cultivation medium (Hultberg et al., 2017).
3. No evaporation and cell and heat losses into the environmental around the system.
4. 90 % of POME supplied into the anaerobic digester is generated as biogas effluent and nutrient contents in biogas effluent are sufficient for algae growth (Ahmad et al., 2016).
5. Algae-based biorefinery is retrofitted into palm oil mill and biogas plant, hence the capital cost of the palm oil system is not included into the economic assessment.

Table 2: Summary of the production of effluents from palm oil mill and biogas plant

Parameters	Value	Reference
Fresh fruit bunch (FFB) processed (t/y)	525,600	Sebrang Mill, Sabah, Malaysia
POME : FFB (m^3 POME/t FFB)	0.7	(Rahayu et al., 2015)
POME generated (m^3/y)	367,920	-
CO_2 generated (t/y)	1,592,217	Sebrang Mill, Sabah, Malaysia
Biogas generated per POME supply (m^3 biogas/m^3 POME)	23.334	(Firdaus et al., 2017)
Total biogas generated (t/y)	9,872.8	-
Biogas effluent generated (m^3/y)	331,128	-

Mass and energy balance for each processing stage is conducted based on the data from Table 2 and 3. The facility in the case study is assumed to operate 365 d/y with 16 h of operation daily. Pond design of 300 m length, 5 m wide, and 0.1 depth and 6 PBR's with 50 m^3 of culture volume each are used to determine the production of dry algae. The cultivated algae are then sent to harvesting and dewatering processes to increase the concentration of algae and remove excess water that can lower the efficiency of solvent extraction process. For the harvesting and dewatering process, 85 % and 70 % separation are assumed for flocculation with chitosan and flocculation with alum. The dewatered algae the undergoes extraction process to extract algal oil and further refined into biodiesel and glycerol. The residual algae from the solvent extraction process is combusted to generate electricity. Electricity generated from each chain is determined by multiplying the mass flow of dry residual algae from each chain with LHV of algae. For solvent extraction process, 80 % of hexane and 90 % of isopropanol is recycled back into the process to reduce the cost for solvent.

Table 3: Characteristics of algae

Parameters	Value	Reference
Lower heating value of algal biomass after extraction (LHV) (MJ/kg dry biomass)	11.25	(IEA Bioenergy, 2009)
CO_2 requirement (kg CO_2/dry algae produced)	1.83	(Sayre, 2010)
Lipid content (%)	27.5	(Ahmad et al., 2016)
Harvested culture density (kg/m^3)	1,020	(Dassey and Theegala, 2013)
Algal oil density (kg/m^3)	864	(Dassey and Theegala, 2013)

3. Economic assessment

The economic assessment of the design chain is conducted using the data listed in Table 4. For capital cost, a discounted cash flow analysis assuming 20 - year facility lifetime with 10 % discounted rate is conducted. The capital cost is estimated based on the production capacity and equipment material while operating cost includes utility, administrative, labour, and maintenance costs. Based on the amount of CO_2 and biogas effluent generated from the palm oil mill and biogas facility, 112.3 t/y of dry algae is produced when cultivated using open pond while the production of dry algae in tubular photobioreactor is 2,176 t/y. Open pond has low investment cost but low productivity. Conversely, tubular photobioreactor has high production cost but it is efficient and produces high biomass production (Goli et al., 2016).

Table 4: Economic parameters

Parameters	Classification	Value	Unit	Reference
Biogas	Selling price	0.46	USD/m^3	(Socalgas, 2016)
Electricity	Selling price	93.75	USD/MWh	(Idris et al., 2017)
Biodiesel	Selling price	729.12	USD/m^3	(Lane, 2017)
Glycerol	Selling price	1.05	USD/kg	(Rizwan et al., 2015)
Alum	Raw material price	2.07	USD/kg	(Barros et al., 2015)
Chitosan	Raw material price	2	USD/kg	(Rizwan et al., 2015)
Hexane	Raw material price	0.47	USD/kg	(Rizwan et al., 2015)
Isopropanol	Raw material price	1.35	USD/kg	(Alibaba.com, 2017)
Biogas facility	Operating cost	27.65	USD/t	(Zhu et al., 2012)
Algae biorefinery				
Open pond	Capital cost	34,100	USD/ha	(Lundquist et al., 2010)
	Operating cost	14.96	USD/t	(Davis et al., 2016)
Tubular photobioreactor	Capital cost	2,619	USD/m^3	(Hernández-Calderón et al., 2016)
	Operating cost	580	USD/t	(Slade and Bauen, 2013)
Flocculation	Capital cost	2,550	USD/ha	(Lundquist et al., 2010)
	Operating cost	15.66	USD/t	(Gutiérrez-Arriaga et al., 2014)
Centrifugation	Capital cost	42.25	USD/t	(Hernández-Calderón et al., 2016)
	Operating cost	2.34	USD/m^3	(Dassey and Theegala, 2013)
Drying	Capital cost	112.30	USD/t	(Idris et al., 2017)
	Operating cost	134.20	USD/t	(Idris et al., 2017)
Solvent extraction	Capital cost	24,300	USD/ha	(Lundquist et al., 2010)
	Operating cost	4,780	USD/ha/y	(Lundquist et al., 2010)
Base catalysed transesterification and biodiesel refining	Capital cost	9,188	USD/m^3	(Hernández-Calderón et al., 2016)
	Operating cost	110.95	USD/m^3	(Martín and Grossmann, 2012)
Combustion	Capital cost	0.91	USD/MWh	(Idris et al., 2017)

The eight (8) processing pathway alternatives is analysed by evaluating the economics of the network. The techno-economic assessment of the processing design chains is summarised in Table 5. The techno-economic assessment shows that all processing chains except for Chain 3 and Chain 7 produce negative profit value. This is due to the fact that tubular photobioreactor requires high capital and operating costs (for Chain 2, 4, 6 and 8) and high raw material cost for chitosan (for Chain 1, 2, 5, and 8). Based on the material balance conducted around the integrated, the chain with the lowest profit, Chain 2, produces 32.5 m^3/y and 4.1 m^3/y of biodiesel and glycerol, which is significantly low for large scale production while 7,215 MWh/y of electricity is generated from the biomass combustion process. In contrast, Chain 7 yields the highest profit, which is 7.730 x 10^5 USD/y. In comparison, although Chain 1 and 3 require less capital cost than Chain 7, the raw material cost required for Chain 1 and 3 are significantly higher, which is contributed from solvent extraction with hexane process. The revenue for all processing chains are approximately the same, mainly due to the profit from biogas production of 3.95 x 10^6 USD/y.

Table 5: Techno-economic assessment for every processing design chain

Chain	Total operating cost (USD/y)	Total capital cost (USD/y)	Raw material cost (USD/y)	Revenue (USD/y)	Profit (USD/y)
1	1.299 x 10^6	6.520 x 10^4	4.205 x 10^6	4.533 x 10^6	-1.036 x 10^6
2	8.374 x 10^6	1.030 x 10^6	5.074 x 10^6	4.654 x 10^6	-9.824 x 10^6
3	1.122 x 10^6	5.497 x 10^4	3.111 x 10^6	4.430 x 10^6	1.423 x 10^5
4	8.162 x 10^6	1.018 x 10^6	3.753 x 10^6	4.530 x 10^6	-8.403 x 10^6
5	1.333 x 10^6	4.016 x 10^5	3.129 x 10^6	4.593 x 10^6	-2.699 x 10^5
6	8.416 x 10^6	1.436 x 10^6	3.775 x 10^6	4.726 x 10^6	-8.900 x 10^6
7	1.151 x 10^6	3.320 x 10^5	2.224 x 10^6	4.480 x 10^6	7.730 x 10^5
8	8.196 x 10^6	1.352 x 10^6	2.683 x 10^6	4.589 x 10^6	-7.642 x 10^6

Based on the results in Table 5, it can be concluded that integration of palm oil mill with algae-based biorefinery is not feasible due to negative profitability produced from algae processing system. This study does not consider the recycling process of wastewater from dewatering process. The whole process can be further improved by considering the recycling process of wastewater to reduce the raw material (chitosan or alum) and utility cost. The superstructure in the case study is limited to conventional algae processing technologies. The superstructure can be expanded to include more technological processing pathways and optimisation on the integrated system can be conducted to further investigate the integration potentials.

4. Conclusions

The economic potentials of an integrated algae-based biorefinery with palm oil mill for various technological alternative pathways are investigated in this study. The integration of algae-based biorefinery with palm oil mill can increase the economic and environmental advantages of the process through the utilisation of CO_2 from palm oil mill and wastewater from biogas process for algae growth. The integrated process reduces the amount of CO_2 emitted into environment and cost required for water and nutrients supply. The results show that the processing network which comprises of open pond, flocculation with alum and centrifugation, drying, solvent extraction with hexane/isopropanol, base catalysed transesterification of algal oil, and combustion of residual algae produces the highest profit of 7.73 x 10^5 USD/y. Further studies can be done to evaluate the integration potentials including expanding the superstructure network to include more processing technologies, optimising the processing pathways, and evaluating the environmental aspects of the system.

Acknowledgments

The author would like to acknowledge the financial support in the form of research grant by UTM with grant no. Q.J130000.2446.03G62 and UTM Zamalah Scholarship.

References

Ahmad A., Shah S.M.U., Buang A., Abdullah M.A., 2016, Anaerobic Co-cultivation of Multi-algal Species with Oil Palm Empty Fruit Bunches for Mill Effluent Treatment and Biomethane Production, Jurnal Teknologi, 78, 65–73.

Alibaba.com, 2017, Isopropanol price <alibaba.com/showroom/price-isopropanol.html>, accessed 15.05.17.

Barros A.I., Gonçalves A.L., Simões M., C.M. Pires J., 2015, Harvesting techniques applied to microalgae: A review, Renewable & Sustainable Energy Reviews, 41, 1489–1500.

Brennan L., Owende P., 2010, Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products, Renewable & Sustainable Energy Reviews, 14, 557–577.

Daoutidis P., Marvin W.A., Rangarajan S., Torres A.I., 2013, Engineering Biomass Conversion Processes: A Systems Perspective, AIChE Journal, 59, 3–18.

Dassey A.J., Theegala C.S., 2013, Harvesting economics and strategies using centrifugation for cost effective separation of microalgae cells for biodiesel applications, Bioresource Technology, 128, 241–245.

Davis R., Markham J., Kinchin C., Grundl N., Tan E.C.D., Humbird D., 2016, Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion, <nrel.gov/docs/fy16osti/64772.pdf>, accessed 23.06.17.

Firdaus N., Prasetyo B.T., Sofyan Y., Siregar F., 2017, Part I of II: Palm Oil Mill Effluent (POME): Biogas Power Plant, Distributed Generation and Alternative Energy Journal, 32, 73–79.

Goli A., Shamiri A., Talaiekhozani A., Eshtiaghi N., Aghamohammadi N., Aroua M.K., 2016, An overview of biological processes and their potential for CO2 capture, Journal of Environmental Management, 183, 41–58.

Gupta S. Sen, Bhartiya S., Shastri Y., 2014, Model-based optimisation of integrated algae biorefinery, 3rd International Conference on Advances in Control and Optimization of Dynamical Systems, 13th-15th March, Kanpur, India, 1011-1018.

Gutiérrez-Arriaga C.G., Serna-González M., Ponce-Ortega J.M., El-Halwagi M.M., 2014, Sustainable Integration of Algal Biodiesel Production with Steam Electric Power Plants for Greenhouse Gas Mitigation, ACS Sustainable Chemistry & Engineering, 2, 1388–1403.

Hernández-Calderón O.M., Ponce-Ortega J.M., Ortiz-Del-Castillo J.R., Cervantes-Gaxiola M.E., Milán-Carrillo J., Serna-González M., Rubio-Castro E., 2016, Optimal Design of Distributed Algae-Based Biorefineries Using CO2 Emissions from Multiple Industrial Plants, Industrial & Engineering Chemistry Research, 55, 2345–2358.

Hultberg M., Lind O., Birgersson G., Asp H., 2017, Use of the effluent from biogas production for cultivation of Spirulina, Bioprocess and Biosystems Engineering, 40, 625–631.

Idris M.N.M., Hashim H., Lim J.S., Ho C.S., 2017, Economic Assessment of Microalgae-Based CO2 Utilization in Power Plant Sector in Malaysia, Chemical Engineering Transactions, 56, 643-648.

IEA Bioenergy, 2009, Algae - The Future for Bioenergy?, IEA Bioenergy ExCo64 Workshop, 1st October, Liege, Belgium.

Lane J., 2017, Ethanol and biodiesel: dropping below the production cost of fossil fuels?, <biofuelsdigest.com/bdigest/2017/05/18/ethanol-and-biodiesel-dropping-below-the-production-cost-of-fossil-fuels/> accessed 20.06.17.

Lundquist T.J., Woertz I.C., Quinn N.W.T., Benemann J.R., 2010, A Realistic Technology and Engineering Assessment of Algae Biofuel Production <ascension-publishing.com/BIZ/Algae-EBI.pdf> accessed 28.11.2016.

Malaysian Palm Oil Board (MPOB), 2017, Number and Capacities of Palm Oil Sectors July 2017 (Tonnes/year) <bepi.mpob.gov.my/index.php/en/statistics/sectoral-status/179-sectoral-status-2017/803-number-a-capacities-of-palm-oil-sectors-2017.html> accessed 18.06.2017.

Martín M., Grossmann I.E., 2012, Simultaneous Optimization and Heat Integration for Biodiesel Production from Cooking Oil and Algae, Industrial & Engineering Chemistry Research, 51, 7998–8014.

Performance Management & Delivery Unit (PEMANDU), 2013, Palm Oil & Rubber, <etp.pemandu.gov.my/Palm_Oil-@-Palm_Oil_-◘-_Rubber.aspx> accessed 11.28.16.

Rahayu A.S., Karsiwulan D., Yuwono H., Trisnawa I., Mulyasari S., Rahardjo S., Hokermin S., Paramita V., 2015, POME-to-Biogas Project Development in Indonesia <winrock-indo.org/4732.html> accessed 15.05.17.

Rizwan M., Lee J.H., Gani R., 2015, Optimal design of microalgae-based biorefinery: Economics, opportunities and challenges, Applied Energy, 150, 69–79.

Sayre R., 2010, Microalgae: The Potential for Carbon Capture, Bioscience 60, 722–727.

Slade R., Bauen A., 2013, Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects, Biomass and Bioenergy, 53, 29-38.

Socalgas, 2016, Biogas and biomethane, <socalgas.com/for-your-business/power-generation/biogas-biomethane>, accessed 9.13.16.

Zhu, X.F., Chen, D.Y., Zhang, D., 2012, Heat/mass transfer characteristics and nonisothermal drying kinetics at the first stage of biomass pyrolysis, Journal of Thermal Analysis and Calorimetry, 109, 847–854.