ECONOMICAL FEASIBILITY OF BIO-OIL PRODUCTION FROM SEWAGE SLUDGE THROUGH PYROLYSIS

by

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Original scientific paper
https://doi.org/10.2298/TSCI170921258X

Pyrolysis can lower the environmental impacts and improve resource utilization. A multi-stage comprehensive assessment model was developed to assess the economic feasibility of sludge pyrolysis. The indicator of gross process yield was used to evaluate the energy conversion efficiency of the different pathways. A comprehensive techno-economic analysis was used to quantify the technical and economic performance of the pathway through uniform monetary measurement standards. Sensitivity analysis was used to determine the uncertainty and risk. The pathway with the highest gross process yield was selected to assess the feasibility using comprehensive techno-economic analysis considering different value. The estimated break even selling price of bio-oil was very close to the average crude oil of recent five years when considering economic, social, and environmental value. The main key factors affecting the economics of system were crude oil price, bio-oil lower heating value, bio-oil yield, and energy consumption of the pyrolysis process.

Key words: *multi-stage comprehensive assessment, energy conversion efficiency, techno-economic analysis, sensitivity analysis, sludge, pyrolysis*

Introduction

Due to rapid increase in the world population and industrialization, the safe disposal of sewage sludge (biosolids) has raised increasing concerns. Many researchers have focused on the energy and nutrients recovery from sewage sludge. Currently, anaerobic digestion, incineration, gasification, and pyrolysis are main sludge-to-energy management technology [1]. The comparative assessment of these technologies showed pyrolysis seemed to be the optimal treatment technology because it was helpful for the energy savings and high-value added materials production [2]. Moreover, pyrolysis can minimize the volume of sludge [3], release less harmful gases, and immobilize metals in stabilized residue termed as bio-char [4]. Many literatures have studied different reactors, optimized temperatures and catalyst influences on pyrolysis of sew-

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age sludge [5, 6]. Some researchers are trying to develop more economic and efficient microwave-assisted pyrolysis (MAP) unit [7].

Current studies on economic feasibility of sludge pyrolysis, however, are limited. The results of Kim and Parker [8] showed the economic values of the oil produced from primary and digested sludge were estimated as 9.9 and 6.9 cent/kg-ds when the value of oil is 32 cent/kg-oil. The major challenge in economic analysis is that different technologies have different economic, social and environmental performances. Anex *et al*. [9] reported that capital cost for pyrolysis was $200 million to $280 million while for gasification it was $500 million to $610 million. Product value of pyrolysis was reported to be $2.00-$3.00/GGE and for gasification it is $4.50-$5.0/GGE. Therefore, in order to correctly understand and evaluate a certain technology pathway, not only energy efficiency, but also capital cost, operating cost and environmental impacts, and social impacts should be considered at the same time. Karagiannidis and Perkoulidis [10] used four criteria including GHG emissions, energy recovered, material recovered and operating cost and decision support method to analyze different technologies in anaerobic digestion sludge. Ten criteria [11] or six criteria [12] were employed to assess the sustainability of the technologies for the treatment of urban sludge.

However, there is no uniform standard for selecting the criteria and index. What is more, it is difficulty in determining the weights of the multi-criteria when integrated evaluation is applied. In many situations, various aspects for analysis are related. For example, technology development will affect economic performance (*i. e.* reducing the running cost and increasing the profit), environmental impact (*i. e.* mitigating CO_2 emission and decreasing occupied land), and also social acceptability (*i. e.* increasing vacancies and social benefits) [13]. Therefore, in order to help the decision-makers to make the correct decision, new method of comprehensive assessing economic, environmental and social aspects should be developed for assessing the technologies of treating urban sewage sludge.

Model development

Multi-stage comprehensive assessment model

In order to comprehensively assess feasible of the technologies, a multi-stage comprehensive assessment model, gross process yield + techno-economic analysis + sensitivity analysis (GPY + TEA + SA) was developed considering different technologies with different economic, environmental and social performances.

Firstly, the indicator of GPY was used to evaluate the energy conversion efficiency of the different pathways. The GPY is defined as the ratio of the recoverable energy (energy content in the target products *e. g.* bio-oil, bio-char, and bio-gas) to the energy input (including energy input in drying and pyrolysis). Bigger value indicates more feasible process.

Secondly, comprehensive TEA was used to quantify the technical and economic performance of a pathway considering economic impacts, environmental impacts and social impacts. The updated net present value (UNPV) and updated internal rate of return (UIRR) were developed to assess comprehensively the technologies from the perspective of incremental investment, in which the capital cost, operating costs and all kinds of revenues including economic benefits, environmental benefits and social benefits of the project were calculated through uniform monetary measurement standards.

$$\text{UNPV} \quad R\frac{1 \quad (1 \quad i)^{\quad n}}{i} \quad \text{Initial investment}$$

where R is the net cash inflow expect to be received each period, i – the required rate of return per period, and n – the number of periods during which the project is operated and expected to generate cash inflows.

When considering economic value,

R Bio oil income Biogas income P – fertilizer income Operating cost Depreciation (1)

When considering economic value, social value and environmental value.

R (1) Carbon credit fee Sludge disposal saving cost Energy safety cost saving (2)

The UIRR is calculated using the UNPV formula by solving i if the UNPV equals zero. These two economic indicators were calculated based on the cash flows generated by the project during its useful life.

Thirdly, due to the fluctuation of economic parameters, SA was followed after techno-economic results to determine the uncertainty and risk.

Energy conversion efficiency assessment

Assuming two drying pathways (traditional and hydrothermal dewatering) could be selected, and two pyrolysis pathways (MAP and slow pyrolysis) could be selected, which defined four technology pathways. Input energy, recoverable energy and GPY of each technology pathway were listed in tab. 1. The fourth pathway had the highest GPY, and would be selected to assess the feasibility using comprehensive TEA.

Table 1. Energy conversion efficiency of f teourchnology pathways

Technology pathway	Energy input	Energy for drying	Energy for pyrolysis	Recoverable energy	GPY [%]
Thermal drying + pyrolysis	11.044	4.514 [a]	6.53 [c]	13.19 [e]	119.43%
Hydrothermal dewatering + pyrolysis	8.647	2.117 b	6.53	13.19	152.54%
Thermal drying + MAP	6.52	4.514	2.006 [d]	13.15 [f]	201.69%
Hydrothermal dewatering + MAP	4.123	2.117	2.006	13.15	318.94%

Energy input [MJ] = energy for drying + energy for pyrolysis
[a] Calculated value based on the moisture content of sludge and heat of water evaporation
[b] Calculated value based on the moisture content of sludge and [14]
[c, e] Calculated value based on [6]
[d, f] Calculated value based on pilot data in University of Minnesota (UMN)

Comprehensive TEA assessment

Basic process and assumptions of TEA assessment

The pathway with the highest GPY was based on the pilot-scale MAP equipment in UMN. The optimal operating temperature were 450-500 °C. The yield ratio of liquid, char and gas were 35.75 wt.%, 35.52 wt.%, and 28.73 wt.%. The water content of the liquid was about 42%, calculated lower heating value (LHV) of bio-oil was 31.53 MJ/kg, LHV of sewage-char was 8.64 MJ/kg, and LHV of gas was 9.46 MJm^3. The variable operating cost was electric energy consumption of 0.5573 Kwh/kg.

The case was set as the St. Paul wastewater treatment Plant (SPWTP) with 250 million gallons of wastewater, and around 265 dry tons of sludge daily. Basic process for sludge pyrolysis system and boundary for economic analysis was shown in fig. 1. The bio-oil upgrading was not included in economic analysis boundary because current technology for upgrading bio-oil was not economically feasible.

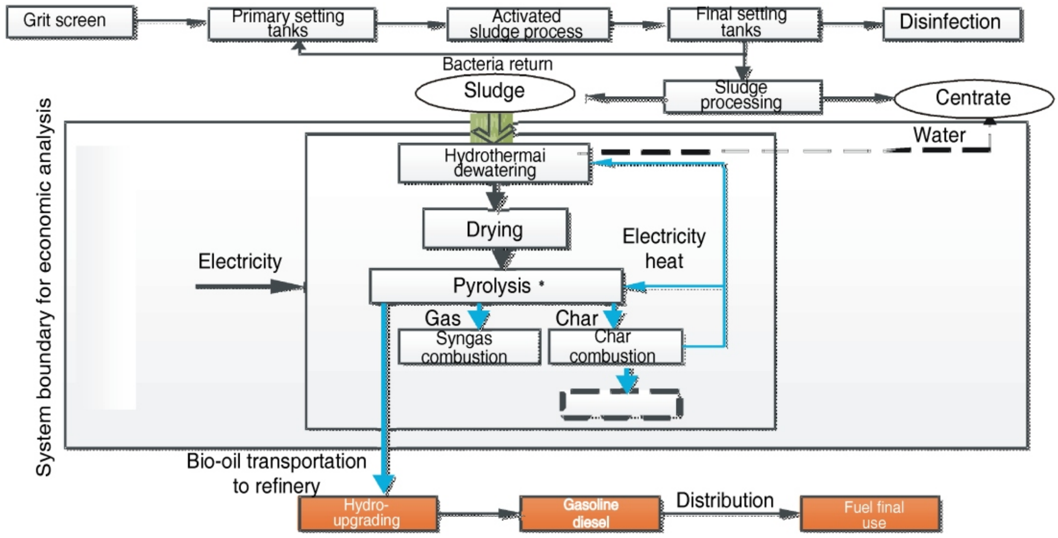

Figure 1. Process schematic for sludge pyrolysis system and boundary for economic analysis

Capodaglio and Callegari [7] believe that MAP of sewage sludge could not only obtain gaseous and liquid fuel production, but the obtained char could be used as P (phosphorus) fertilize. Therefore, assuming bio-oil was sold to a refinery facility, syngas was sold as a heating gas, and biochar was combusted to produce heat for the drying process and the ash was sold for phosphorus fertilizer. In order to prevent corrosion from bio-oil acids, bio-oil storage equipment must be made of stainless steel material.

In order to reduce the uncertainties effect of equipment maintenance and the waste biofuel production industry, this project was assumed to operate 320 days a year.

Parameters estimation methods

– Revenue estimation

Assuming bio-oil and crude oil with same LHV had the same price. Assuming syngas and nature gas with the same LHV had the same price.

Assuming P-rich ash with same phosphate content of phosphorus had the same price. Phosphorus (P) in bio-char from pyrolysis of sewage sludge was 53 g/L. The income tax rate was assumed at 35%.

The total carbon credits were the sum of carbon removal credits minus carbon emissions during waste-based biofuel production [15]. The saving of sludge disposal was not considered because there was no significant reduction on the sludge disposal between incineration and pyrolysis.

Energy safety cost saving was one of social value. Based on data of U.S. Strategic Petroleum Reserve, holding inventory costs were approximately \$0.5-\$1.5 a barrel, assuming \$1a barrel.

Main sources of revenue and their qualifying amounts relative to the capacity of the SPWTP were identified in tab. 2.

– Initial investment estimation

Sludge to bio-oil need hydrothermal dewatering and pyrolysis system, which were estimated based on the experimental scale system and the pilot scale system and adjusted to the

Table 2. Revenue estimates for sludge pyrolysis production system

	Items	Amount	Explanation
1	Carbon removal credits from diesel replaced	46.168.222	3.58 kg CO_2 eq./kg diesel × 265 tons/day × 35.75% × (1-42%) × 31.53/43 × 1000 kg/ton × 320 day year
2	Emissions from electricity consumption	19.896.055	0.421 kg CO_2 eq./kWh × 0.557 kWhkg^{-1} × 265 ton ×1000 kg/ton × 320 day/year
3	Carbon credit	262.722	(1-2)/1000×$10/ton
4	Bio-oil value	94.506X	265 tons /day × 35.75% × (1-42%)×31.53/43 (LHV ratio) × $X /bbl × 7.33 bbl/ton × 320d ay/year
5	P-fertilizer	1.009.630	265 tons × 35.52% × 1000L/ton × 53g/L/17.5% (P Rock conversion)/1000,000,000 × $110/tons × 320day/year
6	Syngas income	1.258.300	265 tons/day × 28.73% × 9.5/35.5(LHV ratio) × 193$/ton × 320 day/year
7	Energy safety cost saving	94.506	265 tons/day × 35.75% × (1-42%) × 31.53/43 (LHV ratio) × $1/bbl × 7.33 bbl/ton × 320 day/year

full capacity levels. Therefore, the scaled up hydrothermal dewatering and pyrolysis system investment were around $7.83 million and $20.61 million. Initial investment estimation relative to the capacity of the SPWTP was shown in tab. 3.

Table 3. Capital cost estimates for sludge pyrolysis production system

Items	Amount ($)	Explanation
Pyrolysis system	20.611.111	Estimation, scale coeffience 0.35
Hydrothermal	7.832.222	Estimation, scale coeffience 0.35
Greenhouse	1.030.556	5% of pyrolysis system costs
Other equipment-pulverizer, storage	618.333	3% of pyrolysis system cost
Total installed cost (TIC)	30.092.222	Sum of above
Field expenses	3.009.222	10% of TIC
Home office and construction fee	4.513.833	15% of TIC
Project contingency	902.766	3% of TIC
Total capital investment (TCI)	38.518.044	Sum of above
Other costs	1.155.541	3% of TCI
Total project investment (TPI)	39.673.586	Sum of above

– *Operating cost estimation*

Operating cost mainly included material, power, labor, maintenance, insurance, and taxes. Due to materials was sludge, materials cost equaled zero. Power was variable operating costs, and others were fixed operating costs. The personnel employed included four operators and one manager. The average salary was selected based on gross annual incomes in the Minnesota industry. Operating cost estimation relative to the capacity of the SPWTP was shown in tab. 4.

Table 4. Operating cost estimates for sludge pyrolysis production system

Items	Amount ($/yr)	Explanation
Drying sludge		Char heating
Electricity for pyrolysis	3.643.672	0.557 kwh/kg × 265 tons/day × 1000 kg/ton × 320 day/year × $0.077/kwh
Total variable operation cost (TVOC)	3.643.672	Sum of above
Manager salary	100.000	1 person
Shift operators salary	160.000	4 persons, 8 hr shift/day, average salary $40,000/pear year
Total salaries	260.000	Sum of above two items
Overhead	130.000	50% total salary
Depiation	1.504.611	TIC/20
Maintenancerec	601.845	2% of TIC
Insurance and taxes	601.845	2% of TIC
Total fixed operating costs (TFOC)	3.098.300	Sum of above
Total operating costs	6.741.972	TVOC + TFOC

Annual depreciation = (cost of asset – salvage value)/estimate useful life, assuming salvage value is zero, estimate useful life is 20 years

Sensitivity analysis method

The SA was used to evaluate the uncertainty of sludge to bio-oil production system. The parameters investigated were crude oil price, carbon credit price, syngas price, P-fertilize price, pyrolysis invest, hydrothermal invest, bio-oil LHV, bio-oil yield, and power consumption for pyrolysis.

Results and discussion

The TEA result considering economic value

In order to remove the impact of short-term price change, four average crude oil equivalent prices, that was 48 months from July 2013 to June 2017 ($67.11), 60 months from July 2012 to June 2017 ($74.14), 24 months from Sept. 2013 to Aug. 2015 ($80.43), 36 months from Sept. 2012 to Aug. 2015 ($85.15) were selected.

When considering economic value, cash flows can be calculated by using eq. (1). The UIRR of system were calculated as 5.62%, 7.92%, 9.85%, and 11.23% respectively, which demonstrated that the alternative crude oil price had an important effect on economic feasibility.

Taking $i = 10\%$, when UNPV = 0, the estimated break even selling price of biofuel was $80.95 /bbl, or $1.93/gallon, or $0.52/L, which demonstrated that the MAP of sludge was not economic feasible when alternative crude oil price below $80.95 /bbl. However, crude oil average price was below $80.95 /bbl in recent years, which showed the MAP of sludge was not economic feasible at present.

The TEA result considering economic value and environmental value

When carbon credit value was considered, cash flows can be calculated by using eq. (2). The UIRR of system were calculated as 6.55%, 8.79%, 10.67%, and 12.03%, respectively.

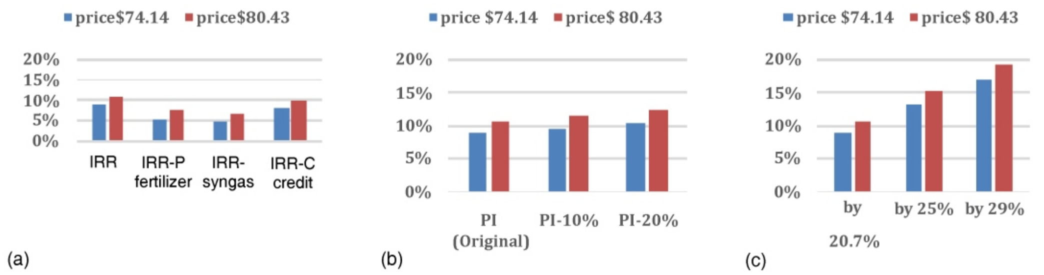

Figure 2. Key factors impacting on UIRR; (a) the impact of co-products utilization, (b) the impact of reducing pyrolysis equipment investment, (c) the impact of improving productivity.

Taking i = 10%, when UNPV = 0, the estimated break even selling price of biofuel was \$78.15 /bbl, or \$1.86/gallon, or \$0.50/L, which was very close to the average price of crude oil in recent five years. The MAP of sludge would be economic feasible and profitable project if other environmental and social value, such as saving of sludge disposal and less emission of harmful gases were calculated.

Assuming the crude oil price of \$74.14 and \$80.43, if P-rich char had not been used as P-fertilizer in the system, the UIRR would be 5.39% and 7.49%. If syngas had not been sold in the system, the UIRR would be 4.49% and 6.58%. If carbon credit had not been calculated in the system, the UIRR would be 7.92% and 9.85% fig. 2(a). These different UIRR results demonstrated co-products utilization and the optimization design of integrated system had an important impact on economic feasibility of sludge pyrolysis system.

The TEA result considering economic value, social value and environmental value

When energy safety cost saving was also considered, cash flows can be calculated by using eq. (2). The UIRR of system were calculated as 6.88%, 9.09%, 10.96%, and 12.31%, respectively. Taking i = 10%, when UNPV=0, the estimated break even selling price of biofuel was \$77.15 /bbl, which was much closer to the average price of crude oil in recent five years. Therefore, it can be concluded the project would be economic feasible if all value of economic, social and environmental factors were considered.

Sensitivity analysis result

The SA result of sludge pyrolysis production system was shown in fig. 3. It can be found that the main sensitive factors of the system were crude oil price, sludge oil LHV, bio-oil yield ratio, energy consumption for pyrolysis.

Key factors improvement had important impact on UIRR. For instance, upgrading the pyrolysis equipment to reduce investment and improving productivity would impact on UIRR, figs. 2(b) and 2(c). It can be found that improving bio-oil yield ratio had more impact on UIRR than reducing pyrolysis equipment investment. Therefore, it can be concluded that more sensitive factor has bigger impacting on the economic feasibility of system.

Discussion

The estimated break even selling price of biofuel based on sludge pyrolysis under different conditions (\$1.92/gallon, or \$0.51/L; \$1.86/gallon, or \$0.50/L; \$1.84/gallon, or \$0.49/L) were very close to the study result of Orfield *et al*. [16] *i. e*. the cost to produce algal bio-oil

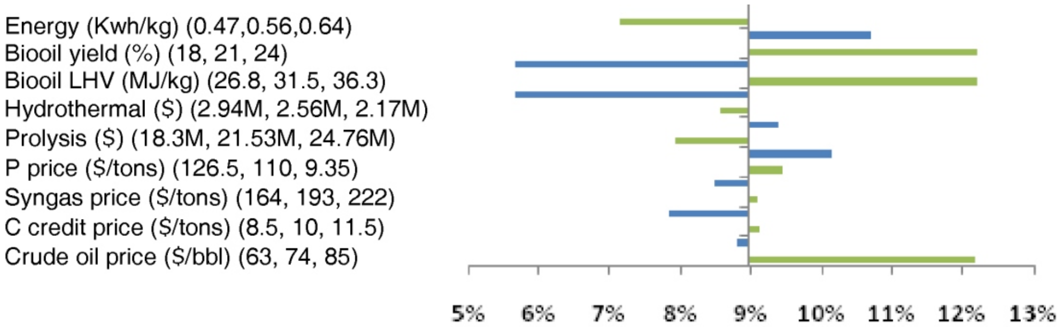

Figure 3. The SA of sludge pyrolysis production system

would need to be less than \$0.55/L to be considered viable with a cost of fossil crude oil of \$80 per barrel. These estimations were less than centrate-based algal biofuel production (\$0.59/L) [15] which indicated the sludge pyrolysis based on the MAP system in UMN had certain feasibility.

Therefore, MAP of sludge can not only lower the environmental impact of wastewater treatment and promote cleaner and more sustainable transportation fuel alternatives, also has economic feasible when considering economic, social and environmental value. Certainly, due to the difference of source, composition, heating value of the sludge and different technology process, the economic results may differ. What is more, there are still some limitations that affect MAP industrialization: uncertainty about the design and development of full-scale microwave-assisted conversion unit, and uncertainty about the actual cost of the process. It is worth pointing out that this study aims at developing a comprehensive assessment method for scientific assessment of the technology for the treatment of urban sewage sludge; thus, the users can change parameters according to the actual conditions.

Conclusion

Pyrolysis was considered as the optimal sludge treatment technology. This study developed a comprehensive assessment method to assess the economic feasibility of sludge pyrolysis. Energy conversion efficiency assessment shown the pathway with the highest GPY was based on the pilot-scale MAP equipment at the UMN. Further comprehensive TEA showed MAP of sludge had economic feasibility when considering economic, social and environmental value. However, the system did not have economic feasibility when environmental and social value was not considered at the present crude oil price. The main key factors affecting the system economic feasibility were crude oil price, bio-oil LHV, bio-oil yield ratio, and energy consumption of the pyrolysis.

Acknowledgment

This work was in part supported by the YUEQI young scholar grants plan of CUMTB, the National Key Research and Development Program of China (2016YFC0801906, 2017YFC0805705), Beijing Education Committee Technology Project of China (SQKM201710016007).

Nomenclature

GGE	– gallon of gasoline equivalent	MACRS	– modified accelerated cost recovery system
HHV	– higher heating value	TPI	– total project investment
LGE	– liter of gasoline equivalent	TCI	– total capital investment
NPV	– net present value	IRR	– internal rate of return
PV	– product value with NPV = 0 in 20 years and 10% IRR		

Reference

[1] Anjum, M, *et al*., Wastewater Sludge Stabilization Using Pre-Treatment Methods, *Process Saf Environ Prot, 102* (2016), July, pp. 615-632
[2] Samolada, M. C., Zabaniotou, A. A., Comparative Assessment of Municipal Sewage Sludge Incineration, Gasification and Pyrolysis for a Sustainable Sludge-To-Energy Management in Greece, *Waste Management, 34* (2014), 2, pp. 411-420
[3] Cao, Y., Pawlowski, A., Sewage Sludge-to-Energy Approaches Based on Anaerobic Digestion and Pyrolysis: Brief Overview and Energy Efficiency Assessment, *Renew Sust Energ Rev., 16* (2012), 3 pp.1657-1665
[4] Jin, J., *et al*., Influence of Pyrolysis Temperature on Properties and Environmental Safety of Heavy Metals in biochars Derived from Municipal Sewage Sludge, *Journal of Hazardous Materials, 320* (2016), Dec., pp. 417-426
[5] Ma, W., *et al*., Supercritical Water Pyrolysis of Sewage Sludge, *Waste Management, 59* (2017), Jan., pp. 371-378
[6] Chang, F., *et al*., Pilot-Scale Pyrolysis Experiment of Municipal Sludge and Operational Effectiveness Evaluation, Energy Sources, Part A: Recovery, *Utilization, and Environmental Effects, 38* (2016), 4, pp. 472-477
[7] Capodaglio, A. G, Callegari, A., Feedstock and Process Influence on Biodiesel Produced from Waste Sewage Sludge, *Journal of Environmental Management*, On-line first, https://doi.org/10.1016/j.jenvman.2017.03.089
[8] Kim, Y., Parker, W., A Technical and Economic Evaluation of the Pyrolysis of Sewage Sludge for the Production of Bio-Oil, *Bioresource Technology, 99* (2008), 5, pp.1409-1416
[9] Anex, R. P., *et al*., Techno-Economic Comparison of Biomass-to-Transportation Fuels via Pyrolysis, Gasification, and Biochemical Pathways, *Fuel, 89* (2010), Suppl. 1, pp. S29-S35
[10] Karagiannidis, A., Perkoulidis, G., A Multi-Criteria Ranking of Different Technologies for the Anaerobic Digestion for Energy Recovery of the Organic Fraction of Municipal Solid Wastes, *Bioresource Technology, 100* (2009), 8, pp. 2355-2360
[11] An, D., *et al*., Multi-Criteria Sustainability Assessment of Urban Sludge Treatment Technologies: Method and Case Study, *Resources Conservation and Recycling, 128* (2018), Jan., pp. 546-554
[12] Ren, J., *et al*., Urban Sewage Sludge, Sustainability, and Transition for Eco-City: Multi-Criteria Sustainability Assessment of Technologies Based on Best-Worst Method, *Technological Forecasting and Social Change, 116* (2017), Mar., pp. 29-39
[13] Levac, M., *et al*., Three-Dimensional Analysis of Fluid Flow and Heat Transfer in Single-and-Two-Layered Micro-Channel Heat Sinks, *Heat Mass Transfer, 47* (2011), 11, pp. 1375-1383
[14] Wang, L., *et al*., Hydrothermal Treatment Coupled with Mechanical Expression at Increased Temperature for Excess Sludge Dewatering: Influence of Operating Conditions and the Process Energetics, *Water Research, 65* (2014), Nov., pp. 85-97
[15] Xin, C., *et al*., Comprehensive Techno-Economic Analysis of Wastewater-Based Algal Biofuel Production: A Case Study, *Bioresource Technology, 211* (2016), Jul., pp. 584-593
[16] Orfield, N. D., *et al*., A GIS Based National Assessment of Algal Bio-Oil Production Potential through Flue Gas and Wastewater Co-Utilization, *Biomass and Bioenergy, 63* (2014), Apr., pp. 76-85

Paper submitted: September 21, 2017
Paper revised: November 21, 2017
Paper accepted: November 22, 2017