CHEMICAL ENGINEERING TRANSACTIONS

VOL. 89, 2021

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-87-7; **ISSN** 2283-9216

DOI: 10.3303/CET2189016

Synergy Effect of Collaboration between Wastewater Treatment Plant and Municipal Solid Waste Incinerator in Smaller Municipality

Ryota Kikuchi[a], Kazuyuki Oshita[a,*], Masaki Takaoka[a], Kazue Shibata[b]

[a] Department of Environmental Engineering, Graduate School of Engineering, Kyoto University, C-1-3, Kyoto Daigaku katsura, Nishikyo-ku, Kyoto, 615-8540, Japan
[b] Technical Research & Development Center, Sanki Engineering Co., LTD. 7-10-1, Chuorinkan, Yamato-shi, Kanagawa, 242-0007, Japan
oshita@epsehost.env.kyoto-u.ac.jp

In recent years, in addition to establishing a decarbonized society worldwide, a depopulation has become a serious problem especially in smaller municipalities in Japan. Wastewater and municipal solid waste (MSW) treatment are responsibilities of municipalities; both are separately treated in Japan. Wastewater treatment plants (WWTPs) and MSW incinerators (MSWIs) must become more cost-efficient and environmentally responsible. This study focuses on the collaboration between a WWTP and a MSWI in smaller municipalities in Japan. A mass and elemental balance, operating costs and greenhouse gas (GHG) emissions calculation model was developed to evaluate MSW collection and transportation, the WWTP, and the MSWI in model cities with populations of 50,000 (small) and 100,000 (medium). Various treatment scenarios for MSW and sewage sludge were evaluated, including collection of 45 % of all kitchen waste by disposers to the WWTP (Case 1); co-combustion of MSW and dewatered sludge in the MSWI (Case 2); co-digestion of thickened sludge, all kitchen waste, and 60 % of all paper waste in MSW (Case 3); and no cooperation (Case 0, the base case), in terms of operating costs and GHG emissions to identify the most effective plan. The combination of Case 1 and 2 optimally reduced operating costs by 14 % compared to Case 0 in both cities. From the perspective of GHG emissions, the combination of Case 2 and 3 provided the lowest emissions from both small and medium cities: the reductions were 29 % and 33.2 %. Disposers and co-digestion minimized operating costs and GHG emissions, in addition to co-combustion which also contributed to both operating costs and GHG emissions.

1. Introduction

The Japanese population is aging, and its numbers are declining. The population and the proportion aged over 65 y were 126 M and 28.4 % in 2019; these values will be 106 M and 36.8 % in 2045 (Japan Cabinet Office, 2020). Depopulation and aging are especially severe in small (less than 50,000 people) and medium (less than 100,000) municipalities, which constituted 69 % and 83 % of all municipalities in 2015 (e-Stat, 2019). Over 40 % of such inhabitants will be 65 y of age in 2045 (IPSS, 2018); this figure is higher than the current total number of Japanese residents. Aging is associated with labour shortages and financial difficulties, inevitably compromising municipal solid waste (MSW) and wastewater treatments; these treatments must become more efficient.

In recent years, sewage sludge production has stabilized at approximately 2.3 Mt (dry base) annually (Japan MLIT, 2021) and the amount of MSW has been decreasing (Japan MOE, 2020). Existing municipal solid waste incinerators (MSWIs) may have excess capacity; new MSWIs will be underworked because of the decline in MSW and depopulation. These excess capacities can be used to incinerate sewage sludge with MSW. Takaoka et al. (2014) calculated the mass and heat balances of MSWIs and wastewater treatment plants (WWTPs) in megacities when these facilities operated separately or together. Co-combustion of MSW and sewage sludge, and co-digestion of kitchen waste and sludge greatly reduced life cycle costs, energy consumption, and greenhouse gas (GHG) emissions, in comparison with independent operation of the plants. Nakakubo et al. (2017) evaluated the effects of various collaborations between MSWIs and WWTPs in cities with populations of

Paper Received: 29 April 2021; Revised: 14 September 2021; Accepted: 20 November 2021
Please cite this article as: Kikuchi R., Oshita K., Takaoka M., Shibata K., 2021, Synergy Effect of Collaboration between Wastewater Treatment Plant and Municipal Solid Waste Incinerator in Smaller Municipality, Chemical Engineering Transactions, 89, 91-96 DOI:10.3303/CET2189016

over 1 M. Co-combustion of dried sludge and MSW, co-digestion of sludge and kitchen waste, and sludge carbonisation decreased GHG emissions, compared with independent treatments. Chen et al. (2019) also compared co-incineration of sewage sludge and MSW with each mono-incineration of them in China, in terms of environmental, energy, and economic aspects. This paper focused on the city with populations of about 10 M and MSWIs in the co-incineration scenario were able to incinerate a total of 1,500 t/d of MSW and SS. The integrated treatment emitted less GHG mainly because of electricity and heat generation, and provided more advantages of costs. Effects on climate change, human health, ecosystem quality and resources were also analysed in this paper. In addition to co-combustion and co-digestion, composting green and food waste was revealed to profit, and emit lower GHG emissions than landfilling them by 90% (Kamyab et al., 2015). It was shown from these works that treating different kinds of waste at the same time generated synergy.

Although these studies focused principally on only large cities, few works have explored MSWI and WWTP cooperation in smaller municipalities. Expansion of MSWI and WWTP treatment areas reduces costs, but not all small and medium facilities can expand their operations (for geographic and political reasons). It is increasingly important for such MSWIs and WWTPs to cooperate. The effect of collaboration in smaller municipalities could be different from that in larger municipalities.

In this study, the cooperation of MSWI and WWTP including diversion of kitchen waste into wastewater through disposers; co-digestion of thickened sewage sludge, kitchen waste, and paper waste (via methane fermentation); and co-combustion of MSW and dewatered sewage sludge were evaluated in terms of operation costs and GHG emissions. A model city was set up to express the pure effects of each cooperation. Three models of MSW collection and transportation, as well as an WWTP and a MSWI were used to simulate the mass balances of MSW and wastewater. Comparative assessment was done between separate MSWI and WWTP operation (the base case), and scenarios featuring single and multiple cooperation, in terms of operating costs and GHG emissions.

2. Methods

2.1 Model cities

This study focused on Japanese cities with populations of 50,000 and 100,000 people. Both municipalities were assumed to be gridded squares with no hills featuring even structures and population distributions with a MSWI and a WWTP in the centres and at edges.

Table 1 shows the sewage influent to the WWTP (JSWA, 2016); these averaged 19,475 and 41,389 m^3/d for cities of 45,000 to 55,000 and 90,000 to 110,000 people. Elemental composition of influent consisted of total organic carbon (TOC), total nitrogen (TN), total hydrogen (TH), total oxygen (TO), total sulfur (T-S) and total phosphorus (TP). After the calculation of these elements, total solid (TS), suspended solid (SS), dissolved solid (DS), volatile suspended solid (VSS), volatile dissolved solid (VDS), fixed suspended solid (FSS) and fixed dissolved solid (FDS) were also calculated for the WWTP system operating at a steady state. The concentration of TN and TP in influent were described by JSWA (2016); and the T-S value was described by Ishikawa et al. (1998); the other values were described by Shomura et al. (2009).

Of all MSW, 80 % was collected and incinerated in the MSWI as combustible waste in Japan. 36.4 t/d and 72.8 t/d of the combustible waste was treated in each city based on the reported MSW-generation rate between population of 50,000 and 100,000 by Japan MOE (2020): 0.91 kg/d/capita. Table 2 shows MSW compositions and characteristics. Weight percentage, water, combustible and ash contents and elemental compositions were quoted from many references including raw data from small and medium sized municipalities (e.g., Matsuto and Ishi, 2011).

Table 1: Influent quality to the WWTP

Items	Unit	Value	Items	Unit	Value	Items	Unit	Value	Items	Unit	Value
TS	mg/L	600	TOC	mg/L	100	TH	mg/L	24	T-S	mg/L	26.8
SS	mg/L	150.1	POC	mg/L	50	PH	mg/L	12	PS	mg/L	2.7
DS	mg/L	449.9	DOC	mg/L	50	SH	mg/L	12	S-S	mg/L	24.1
VSS	mg/L	126.1	IC	mg/L	100	TO	mg/L	65.2	TP	mg/L	5
VDS	mg/L	229.9	TN	mg/L	40	PO	mg/L	48.1	PP	mg/L	2.5
FSS	mg/L	24	PN	mg/L	13.3	SO	mg/L	17.1	SP	mg/L	2.5
FDS	mg/L	220	SN	mg/L	26.7						

POC, particulate organic carbon; DOC, dissolved organic carbon; IC, inorganic carbon; PN, particulate nitrogen; SN, soluble nitrogen, PH, particulate hydrogen; SH, soluble hydrogen; PO, particulate oxygen; PS, particulate sulfur; S-S, soluble sulfur; PP, particulate phosphorus; SP, soluble phosphorus.

Table 2: Composition and characteristics of MSW

Composition	Weight percentage (wt%)[a]	Weight percentage (wt%)[b]	Water content (%W.B.)	Combustible content (%W.B.)	Ash content (%W.B.)	C (% D.B.)	H (% D.B.)	O (% D.B.)	N (% D.B.)	S (% D.B.)	Cl (% D.B.)
Paper waste	28.57	32.70	28.90	66.94	4.16	49.82	7.24	41.98	0.36	0.24	0.36
Kitchen waste	45.21	30.30	82.09	15.61	2.31	56.30	7.87	30.46	3.75	0.50	1.12
Fiber	4.34	5.01	22.10	76.78	1.12	54.66	6.98	34.59	2.44	0.44	0.89
Wood	4.92	13.54	53.00	34.39	12.61	51.99	6.64	39.49	1.44	0.22	0.22
Plastic	14.29	16.03	25.10	69.83	5.07	74.65	10.48	10.94	1.15	0.35	2.42
Rubber	1.79	1.21	7.18	84.79	8.03	67.34	9.38	14.47	6.65	1.85	0.31
Glass	0.23	0.15	3.00	0	97.00	0	0	0	0	0	0
Metal	0.44	0.73	10.00	0	90.00	0	0	0	0	0	0
Ceramics	0.21	0.34	3.00	0	97.00	0	0	0	0	0	0

W.B., wet base; D.B., dry base; C, carbon; H, hydrogen; O, oxygen; N, nitrogen; S, sulfur; Cl, chorine.
[a]Weight percentage of MSW in the small municipality.
[b]Weight percentage of MSW in the medium municipality.

2.2 System boundaries and scenarios

The MSW collection and transportation systems studied, as well as MSWI and WWTP, are shown in Figure 1. The costs of facility construction and garbage trucks (set-up costs) were not considered in this study.
The scenarios of Table 3 were evaluated. In Case 0 (the base case), the MSWI and WWTP operate separately. For Case 1, 45 % of kitchen waste was transported to the WWTP with influent using disposers (Japan MLIT, 2005). In addition to integration of MSW and wastewater treatments, disposers aid MSW collection in an aging society, reducing the amount of household waste and the frequency of disposal. In Case 2, dewatered sludge generated in the WWTP was co-combusted with MSW in the MSWI. In Case 3, thickened sludge, kitchen waste, and paper waste were co-digested. All kitchen waste and 60 % of all paper waste in MSW were isolated (via mechanical separation) after collection and transportation (Kubota Co., Ltd, 2019), then anaerobically digested with thickened sludge (methane fermentation). Case combinations 1 + 2, 2 + 3, 1 + 3 and 1 + 2 + 3 were also evaluated.

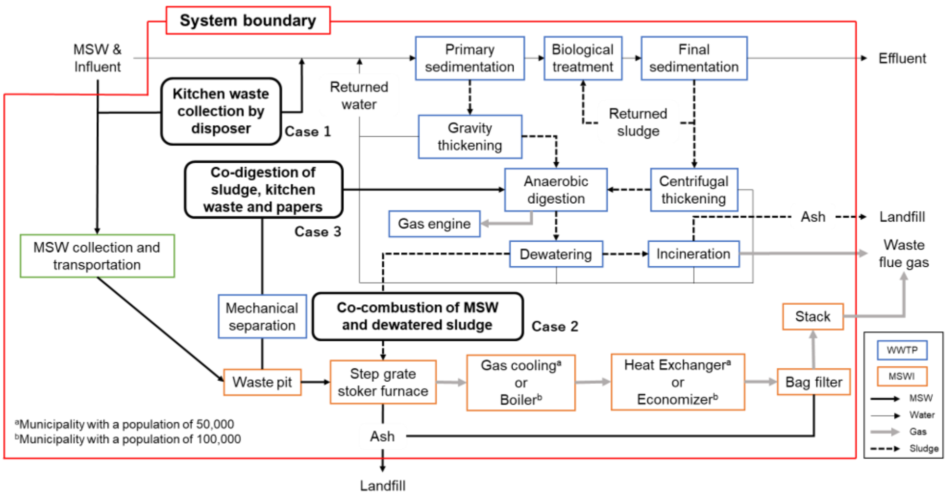


Figure 1: Flow diagram and system boundary of MSW and wastewater treatment in this study

Table 3: Scenarios considered in this study

Case	0	1	2	3	1 + 2	1 + 3	2 + 3	1 + 2 + 3
Disposer	-	O	-	-	O	O	-	O
Co-combustion of MSW and sludge	-	-	O	-	O	-	O	O
Co-digestion of sludge, kitchen waste and paper waste	-	-	-	O	-	O	O	O

2.3 Models and indicators

A combined MSW and WW treatment mass balance model integrated by elemental balance was developed in this study, in accordance with the methods of MSW collection and transportation described by Ishikawa (1996), the WWTP described by Shomura (2009), and the MSWI described by Kuribayashi (2004). Operating costs and GHG emissions were calculated in each scenario using results of the MSW and WW mass balance calculation. Each elemental balance of wastewater in a process was calculated by equation (1), and its results were used for calculation of total solids (TS, SS, DS, VSS, VDS, FSS and FDS) of wastewater, and sludge and effluent for each process in the WWTP under steady-state conditions. Concentration of each element is represented by *e*, *f* is flow rate for each process, *i* represents each element like C, N, H, O, S and P, *j* represents each process, α, β, and γ are proportion of transition to solid, liquid, and gas. The left-hand and right-hand sides represent input and output.

$$e_{ij} \cdot f_j = \alpha \cdot e_{ij} \cdot f_j + \beta \cdot e_{ij} \cdot f_j + \gamma \cdot e_{ij} \cdot f_j \quad (1)$$

The amount of MSW collected by garbage trucks was calculated because this varied according to disposers use/non-use. Based on the chemical equation for stoichiometric combustion and equivalence ratio, ash, waste flue gas, and combustion air generated from incineration were also calculated in the MSWI. In the WWTP, biogas produced by anaerobic digestion of sludge, kitchen waste, and paper waste was used to generate electric power and heat by the gas engine. The MSWI medium city generated electric power by steam produced by waste heat, while the MSWI of small city did not. This was because small scale MSWIs were not expected to generate electricity efficiently. Chemical reagents were used to treat sludge and waste flue gas. Fuel was employed to combust dewatered sludge in the WWTP and by the garbage trucks.

On June 7, 2021, the exchange rate was 110 JPY/USD and used for costs calculation. Consumption of the electric power, fuel and chemical reagents, and amount of landfill were calculated from the results of mass balance calculation and each intensity. Labour, maintenance, and repair costs were considered to calculate the operating costs, in addition to the electric power, fuel, and chemical reagents costs, which were calculated using by each unit cost. The electric power consumed by the MSWI and WWTP was priced at 0.1363 USD/kWh. The unit price of electric power generated from biomass and non-biomass in an MSWI and biogas in a WWTP are set by the Feed-in Tariff regime in Japan at 0.1545, 0.0727, and 0.3545 USD/kWh.

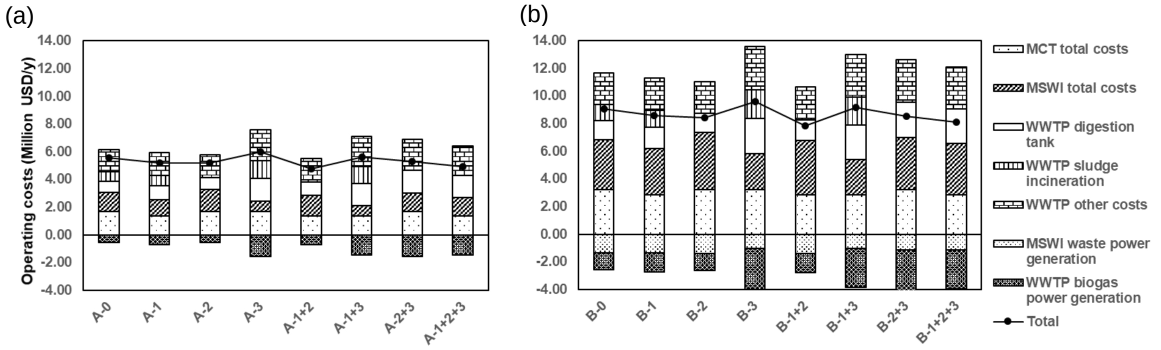
GHG emissions (direct and indirect CO_2, CH_4, and N_2O) were considered based on the results of mass balance calculation, as was the recovery from generated electricity. CH_4 and N_2O emissions were converted to CO_2 equivalents using the global warming potential (100 y): biomass-derived CO_2 was excluded as carbon neutral. Direct emissions included GHG emissions generated when MSW and sludge were incinerated, as well as when fuel was consumed. Emissions associated with electricity consumption and the use of chemical reagents were regarded as indirect emissions.

Electric power was produced by waste heat in the MSWI and biogas in the WWTP; such power was considered to recover some costs and GHG emissions. Material flows, operating costs, and GHG emissions were calculated for the scenarios of Table 3.

3. Results and discussion

3.1 Operating costs

Figure 2a (Case A) and Figure 2b (Case B) show the operating costs for each scenario in small and medium cities. The total costs showed quite similar trend in both cities. Compared with Case A-0, 6.4 % of the total costs were decreased in the entire system in Case A-1 (disposer) because kitchen waste collection via disposers led to reduction of MSW collection and transportation costs in the small city. Furthermore, the MSWI inflow decreased by 20.3 %, reducing operational costs of the MSWI by 14.4 %. When Case B-0 and B-1 were compared, the cost reduction was similar to the reduction between Case A-0 and A-1. When Case B-0 and B-2 were compared, the MSWI inflow increased by 25 % in Case B-2 because of dewatered sludge. Sludge mono-incineration was not required in the WWTP due to co-combustion. Case B-2 (co-combustion) reduced the total costs of the entire system by 7.4 %. The total costs of the entire systems in Case B-3 (co-digestion) were 5.6 % greater than that in Case B-0. The MSWI costs decreased by 30 % considering the reduced MSWI inflow, while biogas recovery in the WWTP rose 2.4-fold, the cost increased for sludge mono-incineration and digestion in the WWTP increased more. Operating costs of Case B-2+3 was lower than that of Case B-0 by 5.8 %. Takaoka et al. (2014) concluded that co-combustion of MSW and dewatered sludge, and co-digestion of sludge, kitchen waste and paper waste decreased life cycle costs that included the operating and construction costs by 3.6 %, compared to independent treatment. The values were roughly the same, although the impact may have been smaller because construction costs were taken into account. Kitchen waste collection by disposers and co-combustion of MSW and dewatered sludge (Case A-1+2 and B-1+2) minimized the total costs of the entire systems: approximately 14 % reduction, compared with Case A-0 and B-0.

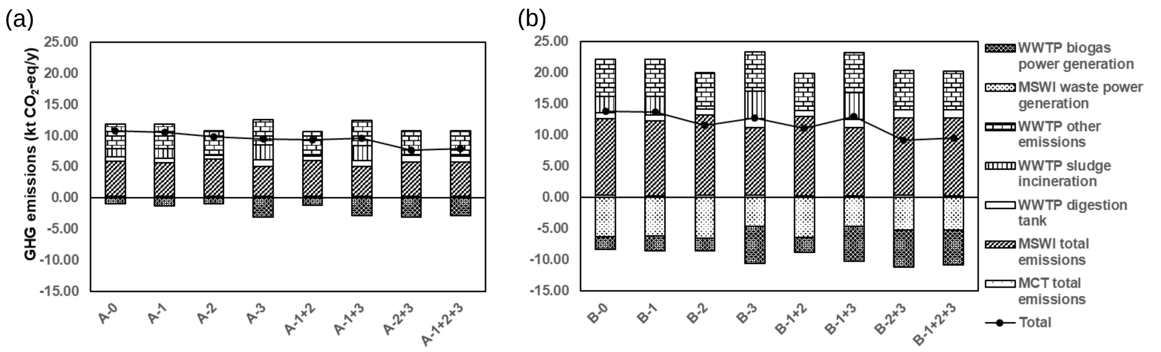


MCT: MSW collection and transportation

Figure 2: Operating costs of each scenario: (a) small city and (b) medium city

3.2 GHG emissions

Figure 3 shows the GHG emissions for each scenario. The GHG emissions of Case A-1 and B-1 (disposer) were very similar to the emissions of Case A-0 and B-0. Disposers markedly reduced the GHG emissions of MSW collection and transportation. These emissions were always less than 3 % of all emissions. The total GHG emissions of Case A-2 and B-2 (co-combustion) decreased by 9.8 % and 16.8 % for both cities, compared with the total GHG emissions of Case A-0 and B-0, because N_2O emissions from sludge mono-incineration and CO_2 emissions from the auxiliary fuel for the sludge mono-incineration disappeared in both WWTPs and the electricity generated by the MSWI of the medium city was slightly increased. For Case A-3 and B-3 (co-digestion), the total emissions of the entire systems reduced by 12.4 % and 7.5 % for small and medium cities. Reduction of GHG emissions by means of biogas power generation was almost three-fold greater than the reduction of GHG emissions in Case A-0 and B-0. The differences between Case A-3 and B-3 values reflect power generation by the MSWI. The electricity generated using paper waste biogas was lower than the electricity generated using paper waste heat in this setting condition. In terms of GHG emissions, the optimized scenarios were Case A-2+3 and B-2+3 (co-combustion and co-digestion) in both cities: 29.0 % and 33.2 % reduction, compared with Case A-0 and B-0. According to Nakakubo et al. (2017), the combination of co-incineration of dried sludge with MSW and co-digestion of sludge and kitchen waste was able to reduce 26 % of GHG emissions, though energy recovery from digestion was not considered. This indicated that the results of Case A-2+3 and B-2+3 was reasonable, although there was slightly difference because of different setting condition. In only MSWIs, the GHG emissions of Case A-2+3 and B-2+3 were almost the same as the emissions of Case A-0 and B-0; there was little difference in the MSWI inflow. The decrease of GHG emissions from sludge mono-incineration exceeded the increase of the digestion, and reduction by biogas recovery was almost three-fold greater than that of Case A-0 and B-0. The most desirable scenario didn't change by population scale, same as operating costs.



MCT: MSW collection and transportation

Figure 3: GHG emissions in each scenario: (a) small municipality and (b) medium municipality

4. Conclusions

In this study, a mass balance calculation model was developed to evaluate MSW collection and transportation, the WWTP, the MSWI and their collaboration in model small and medium cities. Various scenarios of

cooperation were evaluated in terms of operating costs and GHG emissions to identify the most effective plan. In terms of operating costs, combination of kitchen waste collection by disposers and co-combustion of MSW and dewatered sludge (Case A-1+2 and B-1+2) minimized the total costs of the entire systems: about 14 % reduction in both cities, compared with Case A-0 and B-0. Case A-2+3 and B-2+3 afforded the lowest GHG emissions by both cities. Co-combustion was important from the viewpoint of both operating costs and GHG emissions. In addition to co-combustion, disposers and co-digestion would be the best choice for costs and GHG emissions. It was indicated that collaboration between the WWTP and MSWI could be as effective in smaller municipalities as in larger municipalities.
The sensitivity analyses are going to be conducted by changing percentages of kitchen waste collected by disposers, and co-digested paper waste. Analysing its effects on operating costs and GHG emissions will show whether kitchen waste should be collected by disposers, and paper waste should be co-digested or not.

References

Chen G., Wang X., Li J., Yan B., Wang Y., Wu X., Velichkova R., Cheng Z., Ma W., 2019, Environmental, energy, and economic analysis of integrated treatment of municipal solid waste and sewage sludge: A case study in China, Science of the Total Environment, 647, 1433-1443.

e-Stat, 2019, Municipality data, Portal Site of Official Statics in Japan <e-stat.go.jp/en/regional-statistics/ssdsview> accessed 28.01.2021.

IPSS, 2018, Population and Household Projection, Japan National Institute of Population and Social Security Research <ipss.go.jp/site-ad/index_english/population-e.html> accessed 03.02.2021.

Ishikawa M., 1996, A logistic model for post - consumer waste recycling, The society packaging science and technology Japan, 5(2), 119–130, (in Japanese).

Ishikawa S., Matsueda E., Miyashita S., 1998, Material balance of nitrogen, phosphorus, and sulfur in centralized treatment of sewage sludge, <city.yokohama.lg.jp/kurashi/machizukuri-kankyo/kasen-gesuido/gesuido/shori/sokutei/chosa/odeisyori.files/0088_20180827.pdf> accessed 03.06.2021, (in Japanese).

Japan Cabinet Office, 2020, Annual Report on the Ageing Society <www8.cao.go.jp/kourei/english/annualreport/index-wh.html> accessed 28.01.2021.

Japan MLIT, 2021, Toward to the Circulation of Resources and Energy, Ministry of Land, Infrastructure, Transport, and Tourism Japan <mlit.go.jp/mizukokudo/sewerage/crd_sewerage_tk_000124.html> accessed 29.01.2021, (in Japanese).

Japan MLIT, 2005, Reports on the social experiments to introduce disposers, Ministry of Land, Infrastructure Transport, and Tourism Japan, Tokyo, Japan, (In Japanese).

Japan MOE, 2020, Survey Results of Municipal Solid Waste Treatment in Japan, Ministry of the Environment Japan, <env.go.jp/recycle/waste_tech/ippan/index.html> accessed 30.01.2021, (in Japanese).

JSWA, 2018, Japan sewage statistics in 2016 FY, Japan Sewage Works Association, Tokyo, Japan, (in Japanese).

Kamyab H., Goh R.K.Y., Wong J.H., Lim J.S., Khademi T., Ho W.S., Ahmad R., Hashim H., Ho C.S., Lee C.T., 2015, Cost-benefit and greenhouse-gases mitigation of food waste composting: A case study in malaysia, Chemical Engineering Transactions, 45, 577-582.

Kubota Co., Ltd., 2019, Projects for leading waste treatment systems in small and medium sized waste treatment facilities in 2018 FY, (Applicability improvement of combined treatment system with methane fermentation and incinerator to small and medium-sized waste treatment facilities), Osaka, Japan, (in Japanese).

Kuribayashi K., 2004, Life cycle assessment of heavy metals and salts recovery system for melting fly ash, Bachelor Thesis, Kyoto University Faculty of Engineering, Kyoto, Japan (in Japanese).

Matsuto T., Ishii S., 2011, Proximate and Ultimate Analysis for Detailed Composition of Combustible Fractions in Household Waste, Journal of Japan Society of Material Cycles and Waste Management, 22(6), 382–395, (in Japanese).

Nakakubo T., Yoshida N., Hattori Y., 2017, Analysis of greenhouse gas emission reductions by collaboratively updating equipment in sewage treatment and municipal solid waste incineration plants, Journal of Cleaner Production, 168, 803–813.

Shomura S., Oshita K., Takaoka M., Matsumoto T., Morisawa S., 2009, A Comparative Evaluation of Sewage Treatment Systems from the Perspective of Energy Consumption, Proceedings of IWA Sludge Conference 2009, 8th-11th August, Harbin, China.

Takaoka M., Oshita K., Iwamoto T., Mizuno T., 2014, Effect of co-managing organic waste using municipal wastewater and solid waste treatment systems in megacities, Water Science & Technology, 69.6, 1159–1166.