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ORIGINAL ARTICLE

Economic assessment of food waste co-digestion with sewage sludge in five Asian cities

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Abstract

Food waste not only causes waste treatment loading but also leads to loss of resources. Food waste co-digestion with sewage sludge is regarded as one of the optimal technologies to treat food waste and for the recovery of bio-energy and phosphorus. Besides, focus on the recovery rate and efficiency, environmental impacts and other benefits should also be considered when a new technology or policy is evaluated. In this study, the economic and recycling benefits of such treatment technology were assessed in five different cities in Asia. The comprehensive economic assessment was based on life cycle assessment and three kinds of economic benefits, i.e., energy production, P recovery, and greenhouse gas emissions. Hence, the aim of this study is to show the differences in economic benefits from various treatment processes in five cities in Asia. The benefits of food waste co-digestion with sewage sludge were evident from the results of this study. The results indicated that new energy production always dominates the economic values while the economic value from P recovery was relatively low since the P fertilizers are not expensive in Asia. However, differences in economic values were considered for the different Asia cities.

Keywords Food waste · Wastewater · Phosphorus recovery · Environmental assessmentanalysis · Co-digestion treatment process · Life cycle assessment

Introduction

Food waste has emerged as a serious environmental concern in recent years [1–3]. Food waste not only adds to waste treatment loading but also results in the resource loss. Food waste co-digestion with sewage sludge is regarded as one of the optimal technologies to treat food waste and recover bio-energy and phosphorus [4].

Since the industrial revolution, large quantities of phosphorus have been mined from phosphorus rocks, resulting in their quick depletion [5], while the mobilization of the element phosphorus by the global economy has nearly tripled [6], there are no alternative resources to replace the present demand for phosphate rock. Several studies in the past have focused on phosphorus depletion at various spatial scales [7–11]. These studies have indicated that the urban waste treatment system has significant potential for recovery and recycling of P.

Additionally, conversion of food waste to useful energy provides an excellent solution for the treatment of food wastes under the framework of modern food waste management [12]. Anaerobic digestion is not only a feasible food waste treatment pathway but can also convert food waste into energy. Moreover, it is advantageous in terms of low costs and production of small amounts of residual waste [4, 13]. The biogas generated from the treatment of food wastes can be converted to other energy forms, such as, electricity and heat as well as city gas and biogas fuel for use by vehicles [14]. Such research approaches have also been conducted in the field of wastewater management [15–17]. The general methods for treating urban organic waste in the world were summarized in Table 1. The results showed that the technology for combined treatment of two kinds of waste, i.e., food and waste water sewage has special advantages.

During the evaluation of a new technology or policy, the recovery rate, efficiency, environmental impacts, as well as

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Table 1 General sludge and food waste treatment methods

Urban organic waste	Sludge				Food waste				Sludge and food waste mix	
Treatment technique	Stabilization technique		Thickening	Dewatering	Anaerobic digestion	Landfill	Incineration	Composting	Anaerobic digestion	Aerobic digestion
	Anaerobic digestion: mesophilic anaerobic digestion, thermophilic anaerobic digestion	Aerobic digestion: thermophilic aerobic digestion	Gravity thickening, flotation thickening, and mechanical thickening	Drying beds, filter press, belt filter press, thermal drying						
Advantage	Energy consumption is greatly reduced Bioenergy (biogas) can also be recovered Sludge production is low	Simple process and low operating costs The solid–liquid separation effect is good, and the effluent water quality is good	Reduce sludge volume Reduce sludge moisture content	Reduce sludge volume Reduce sludge moisture content	The produced biogas can be recycled Odor problem is easy to control The concentrated filtrate after sludge dewatering can be used as the fertilizer or aquaculture. The treatment effect is stable.	Solve the problem of waste from food waste	Solve the problem of waste from food waste	Resource recycling Composting products are used for agricultural land, which can improve agricultural land	The produced biogas can be recycled Sludge production is low The treatment effect is stable Treat two kinds of waste in the same time	Simple process than anaerobic digestion No odor problem Treat two kinds of waste in the same time
Disadvantage	Sensitive to environmental factors such as temperature and pH Odor problem The removal effect of ammonia nitrogen is not good	Need larger sewage plant area The mechanical dewatering performance of the digested sludge is poor	No removal efficiency for sludge organic matter	No removal efficiency for sludge organic matter	The economic benefits of biogas power generation need to be assessed	High oil and high salt cause soil pollution No reuse of resources	High oil and high salt lead to reduced combustion efficiency of incinerator No reuse of resources	Need large area Odor problems Compost contains high oil and salt Produce sewage problem.	The technology is more complicated Need to assess economic benefits	The technology is more complicated Need to assess economic benefits No biogas production
References	[34–39]				[40–43]				[15, 30, 36, 44]	

other benefits should be considered. Life cycle assessment (LCA) is a scientific and analytical technique for comparing two or more alternative options within the context of potential environmental impacts [12, 18, 19].

The economic and recycling benefits of such a treatment technology should be assessed and compared in different cities, because local suitable technology should be investigated because of the difference in society, environment and residents' behavior. In this study, the comprehensive economic assessment is based on LCA and three kinds of economic benefits including energy production, phosphorus recovery, and greenhouse gas (GHG) emission were considered. Therefore, the aim of this study is to determine the different economic benefits from various treatment processes in five cities in Asia.

Materials and methods

System scale, study area and data collection

This study aims to analyze economic benefits of the different processing technologies in urban governance; hence the urban samples in this study should have some similar characteristics. This study tried to select the cities in Asia that have similar geographical features and are also highly economically developed cities. After referring to the related literature [20, 21], Taipei, Bangkok, Shanghai, Osaka, and Singapore are the major cities located in Asia and all of these cities are close to the airport and port, so the international business activities are very prosperous in these cities. They also have high population density and heavy business activities. However, the residents' behavior and lifestyle, and urban metabolism and governance are different in these five cities. Hence, it is interesting to compare the economic benefits of food waste co-digestion with sewage sludge in these five Asian cities. These are a few of the main cities in Asia and are representative of the current potential for P recovery rate, energy production, energy consumption, and GHG emissions in Asia. The database for these cities is shown in Table 1. In addition to the city government websites, data were also collected from reports, research studies, and projects [22–28]. Additionally, apart from different levels of development, as shown in Table 2, the cities also presented huge differences in terms of population, wastewater type, etc. The city with the largest population was Shanghai; however, the per-capita wastewater emission in Shanghai was the least among the five cities. On the other hand, although Osaka does not emit the most amount of wastewater; however, the P percentage in wastewater was the largest among the five cities. Therefore, a comprehensive assessment is necessary, especially before the technology is promoted to the application level through policymaking.

Waste treatment technology

Anaerobic sludge digestion is an existing popular technology in Europe [15, 16, 18]. This technology usually has the potential to produce large amounts of digestion gas along with high levels of P recovery.

Thus, anaerobic digestion treatment was used to target both wastewater sludge and food waste. Table 3 indicates the different food waste and wastewater co-digesting treatment technology scenarios while Fig. 1 shows the main process of co-digesting treatment technology used for food waste and wastewater in this study. This research integrated the co-digesting treatment technology process for food waste and wastewater from different studies [15, 16, 29, 30]. After integrating the P recovery as well as wastewater and food waste treatment processes from these studies, the wastewater sludge and food waste were treated by an anaerobic digestion system. Additionally, the filter was used for the recovery P. In this study, six different kinds waste treatment methods were generated after recovery of P: (1) compost; (2) cement feedstock; (3) low-temperature carbonization; (4) dry granulation; (5) pyrolysis gasification; and (6) high-temperature incineration. The technology not only recovered P but also produced energy. Moreover, this study also highlighted the uncertainty associated with food waste and wastewater co-digesting treatment technology. Such information could also assist policy formulation. This technology is already used for waste treatment at a plant in Japan [30, 31].

Table 2 Summary of the essential information of five cities in Asia

Item	Osaka	Taipei	Shanghai	Singapore	Bangkok
Population (million)	2.87[a]	2.30[b]	18.80[c]	5.54[d]	8.30[c]
Wastewater (L/capita)	102,675[e]	95,192[b]	12,734 [h]	54,750[g]	13,193[j]
Food waste (ton/capita)	0.09[e]	0.02[b]	0.01 [k]	0.12[i]	0.07[j]
P in wastewater (g/capita)	1.300[e]	1.082[f]	0.082 [h]	0.270 [l]	0.003[j]
P in food waste (g/capita)	0.250[e]	0.378[f]	1.699 [k]	0.607 [m]	0.055[j]

References: [a][45], [b][46], [c][24], [d][47], [e][17], [f]Investigated and analyzed by this study, [g][48], [h][26], [i][49], [j][22], [k][12], [l][27], [m][28]

Table 3 Different scenarios of food waste and wastewater co-digesting treatment technology in this study

Scenario	Sludge conversion	Phosphorus recovery	Point in process for P recovery
(1)	Compost	MAP method[b]	Filtrate water
(2)	Cement feedstock	MAP method	Filtrate water
(3)	Low-temperature carbonization	MAP method	Filtrate water
(4)	Dry granulation	MAP method	Filtrate water
(5)	Pyrolysis gasification	MAP method and alkaline extraction	Filtrate water and ash
(6)	High-temperature incineration	MAP method and partial-reduction melting	Filtrate water and ash
(0)[a]	High-temperature incineration without phosphorus recovery	None	None

[a] Scenario 0 means current treatment process

[b] Magnesium ammonium phosphate (MAP) method

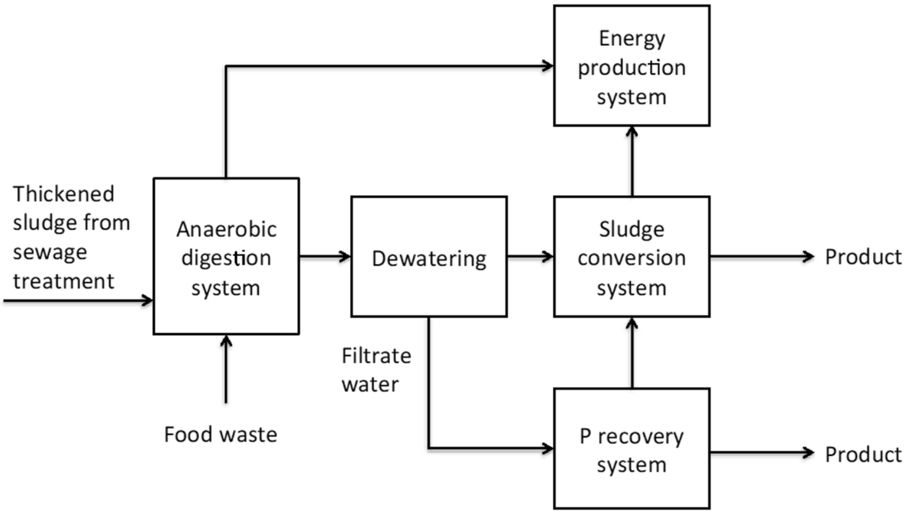


Fig. 1 The main treatment process of food waste and wastewater co-digesting treatment technology in this study

Due to the limitation of five Asian cities data complement state, the assessment situation ignores the energy-use site, the energy consumption of collection waste and energy consumption in delivery, etc. The functional unit was set as the processing capacity to provide waste treatment services for 100,000 people. Most of the method coefficients used in the LCA calculations but the objective of this paper is to determine the trend that can be used for case studies in the other areas. Additionally, this study assumed that the waste comprised household wastewater and food waste.

Results

After collecting data for wastewater and food waste for the five cities, P recovery rates, energy consumption and production were estimated for each city (presented below). Additionally, the GHG emissions and economic benefit were also investigated. Due to data and methodology limitations, some uncertainty ranges were associated with P recovery rate and energy production. Consequently, the net energy production and economic assessment are also likely to show uncertainty.

Energy benefits

Heat and CH_4 were produced during anaerobic digestion of wastewater and food waste. Figure 2 presents energy consumption versus percent phosphorus recovery from six sewage sludge-processing technologies in the five cities. Although the amount of energy produced is different for each city, the energy produce trend in each treatment method is almost the same in every city. This is because the amount of food waste and wastewater produced varied across different cities, therefore, resulting in different amounts of energy produced.

It is essential to consider both energy consumption and the production in this study. The energy production as well as consumption should be balanced while considering energy benefits. Figure 3 presents the net energy production versus percent phosphorus recovery from six sewage

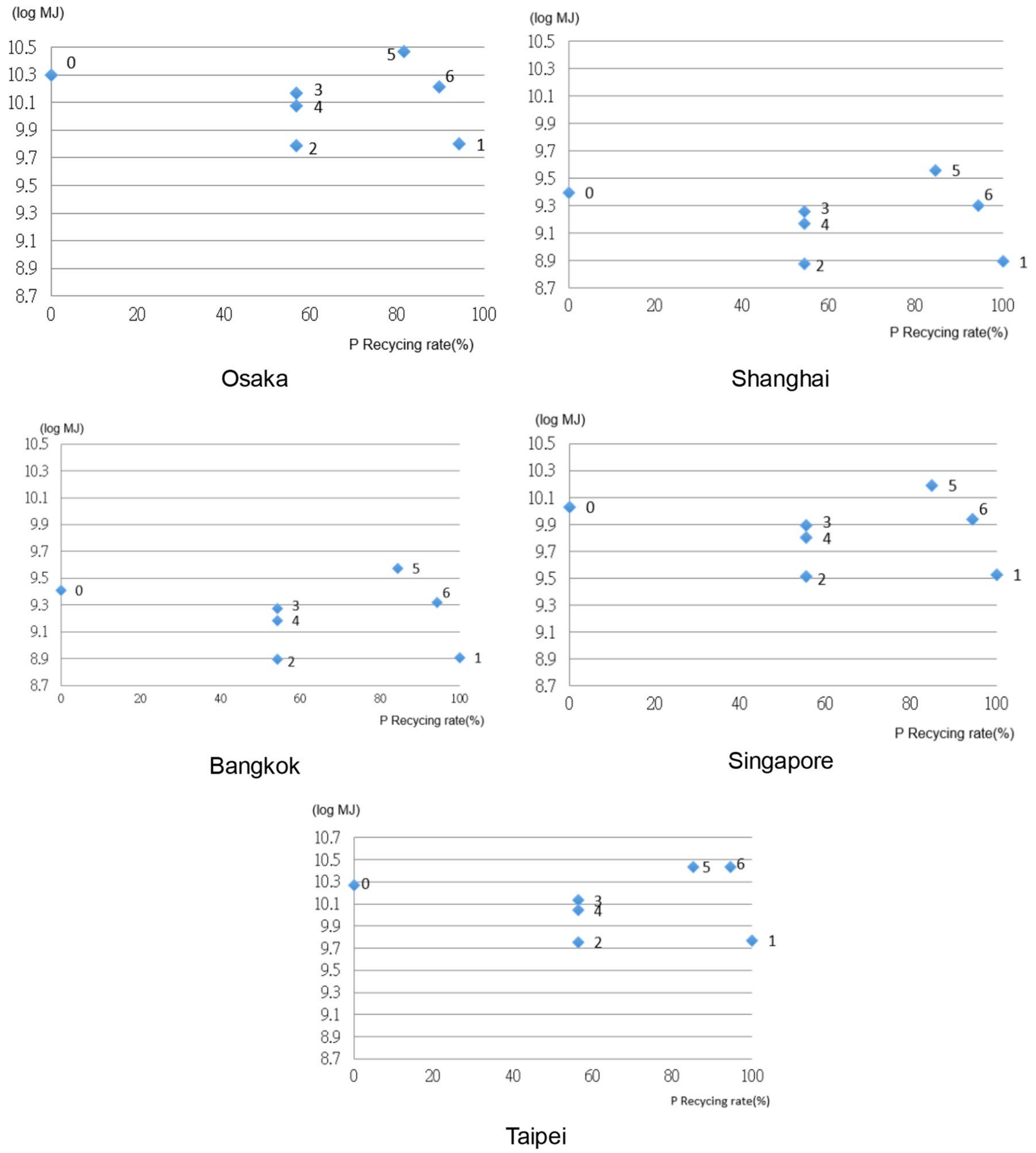


Fig. 2 Energy consumption amount versus percent phosphorus recovery from six sewage sludge-processing technologies in five Asian cities. (1) Scenario 0 means current treatment process. (2) These data were calculated in terms of treatment capacity of 100,000 persons per year

sludge-processing technologies in the five cities. Amongst the six technologies considered for obtaining energy balance, scenarios 1 and 2 showed maximum energy production. Scenario 5 indicated maximum energy costs not only among the six scenarios but also for the five Asian cities. Scenarios 1 and 6 showed higher P recovery rates in comparison to the other scenarios.

Considerations of energy benefits are important for implementation and execution of the waste treatment technology. Several resource recovery scenarios as well as waste treatment technologies exist; however, most of these scenarios are not widely implemented either due to high energy consumption or the need for additional resources. However, a scenario that not only needs less energy but also produces energy, could be used and implemented as part of policy. Figure 4 shows the net energy produced per 1% P recovery from six sewage sludge-processing technologies in the five Asian cities.

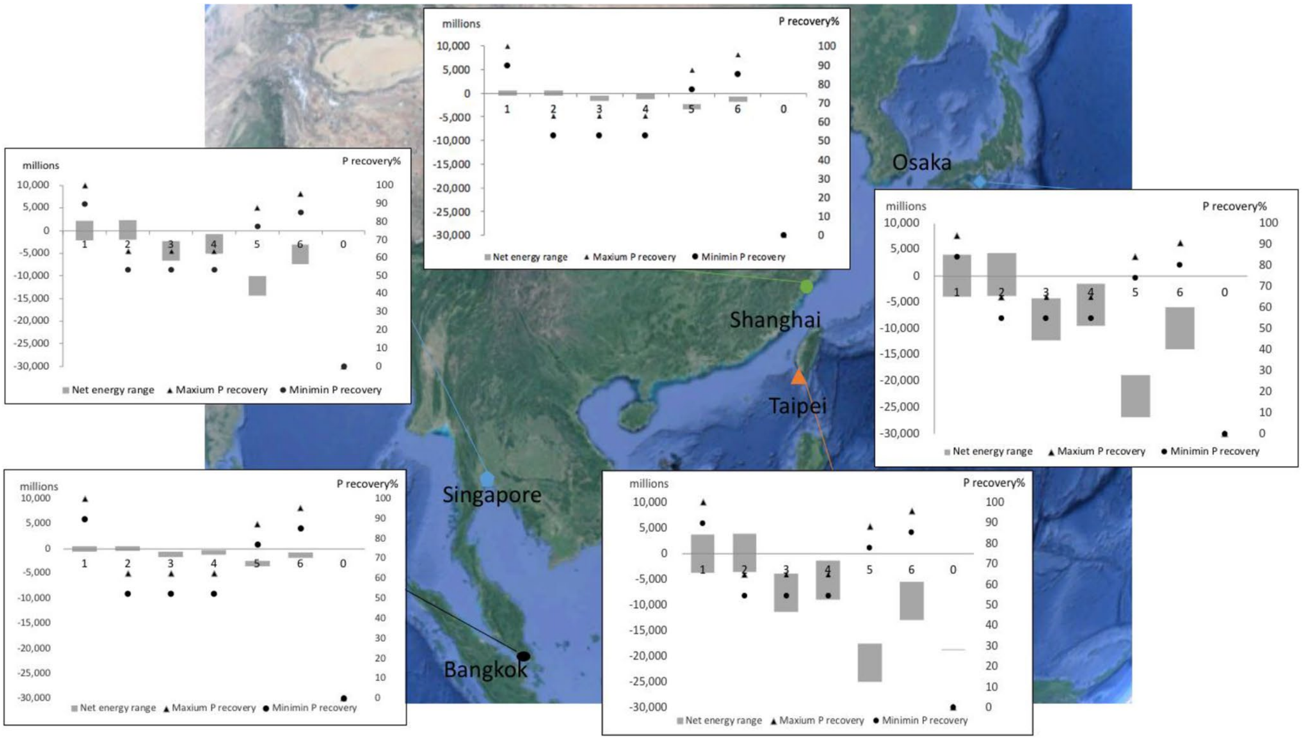


Fig. 3 Net energy product amount versus percent phosphorus recovery from six sewage sludge-processing technologies in five Asian cities (million MJ on left vertical axis). (1) Scenario 0 means current treatment process. (2) These data were calculated in terms of treatment capacity of 100,000 persons per year

The results indicate that scenarios 1 and 2 that combine wastewater and food waste treatment process can potentially result in positive energy benefit. This implies that after the recovery of P from waste filter, the residual waste could be used as compost. Additionally, its use as cement feedstock could create energy-related and monetary benefits. While scenario 2 can produce maximum energy as well as high recovery rate of P, it is not the most optimal due to the associated uncertainty as the policy maker still could accord the risk from the uncertainty to choose the recovery and treatment method.

This study not only considered treatment processes with respect to production and consumption of energy but also the materials used for each treatment process. The results indicate similar energy production values across the different treatment processes. However, a large difference in energy consumption was observed. These results are likely to assist policy formulation for treatment of food waste and wastewater.

The GHG emission

GHG are produced during the wastewater and food waste treatment process. Lower GHG emissions are likely to have less detrimental environment impacts. High-temperature incineration is one of the most commonly used treatment pathways for wastewater sewage and food waste. Due to data limitations, the uncertainty range could not be presented for GHG emissions. However, the likely values are presented in Fig. 5, which presents the amount of GHG emissions versus percent phosphorus recovery from six sewage sludge-processing technologies in the five cities. The results indicate that scenario 1 was the best when the P recovery rate is considered; however, scenario 4 produced the least GHG emissions. On the other hand, the results show that GHG emissions under the current treatment were more than those for the other scenarios considered in this study.

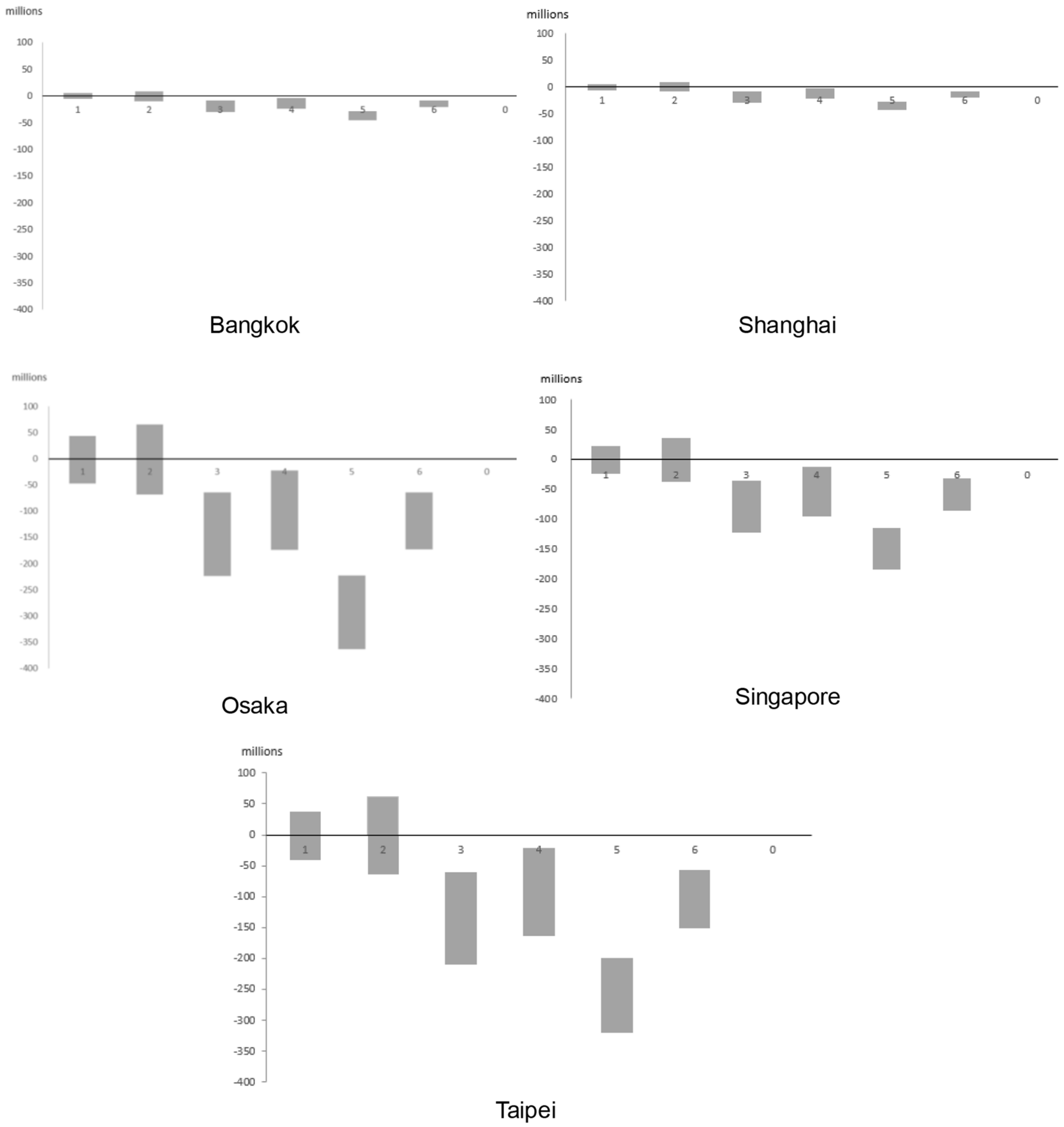
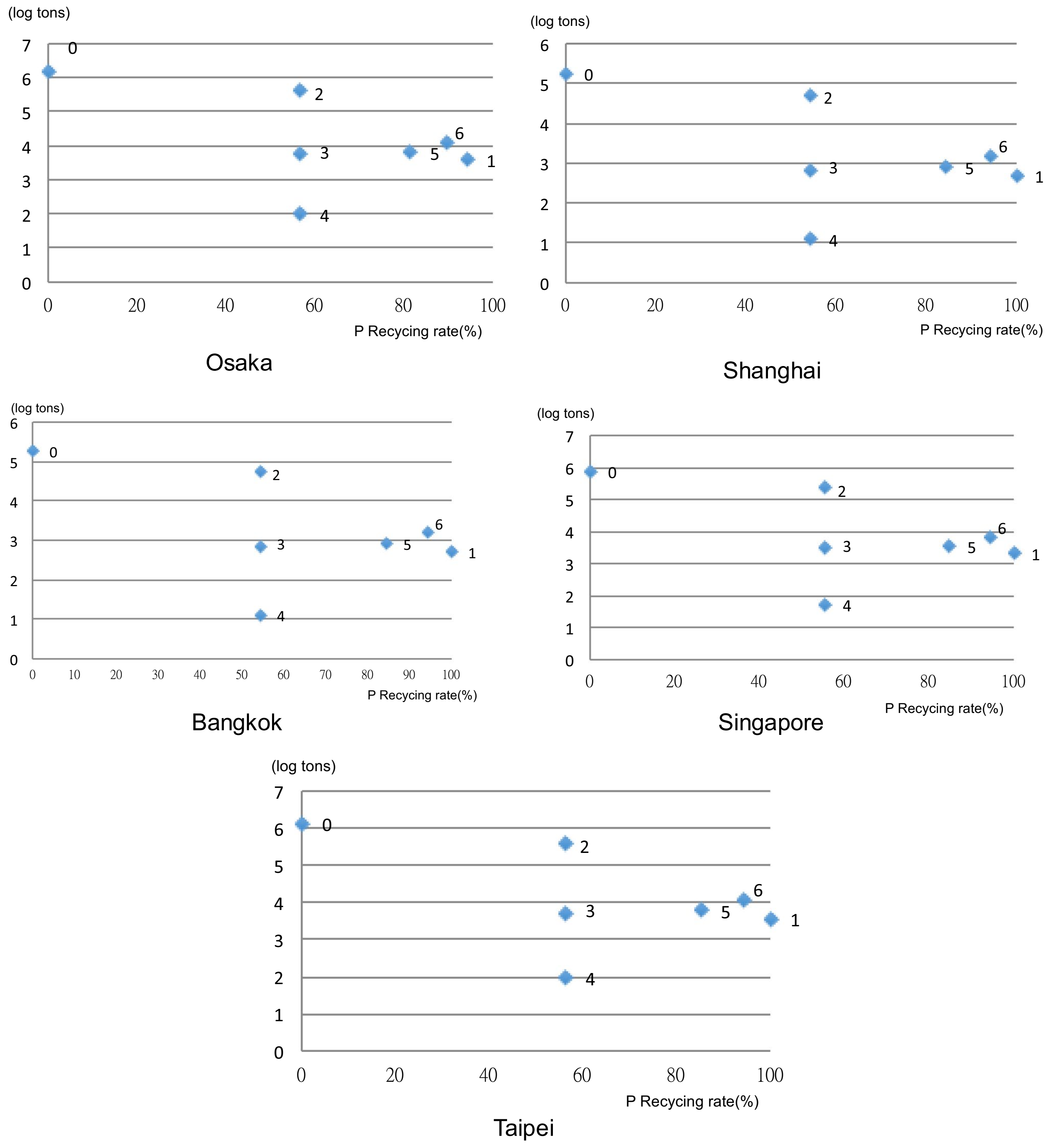


Fig. 4 Net energy produce amount per recovery 1% phosphorus from six sewage sludge-processing technologies in five Asian cities (million MJ). (1) Scenario 0 means current treatment process. (2) These data were calculated in terms of treatment capacity of 100,000 persons per year

Economic benefits

Three kinds of economic benefits including energy production, P recovery, and GHG emissions were considered. Table 4 shows the electronic fee, carbon emission tax, and the P price in the five Asian cities. The electronic fee for each city was obtained from the government dataset, and the household usage price is chosen in this study. Since carbon tax fee is still not implemented in all cities, therefore, those for Taipei, Bangkok, and Singapore were considered to be the same as those for Shanghai [32]. The price of P is calculated as that of the diammonium



Osaka

Shanghai

Bangkok

Singapore

Taipei

Fig. 5 GHG emission amount versus percent phosphorus recovery from six sewage sludge-processing technologies in five Asian cities. (1) Scenario 0 means current treatment process. (2) These data were calculated in terms of treatment capacity of 100,000 persons per year

phosphate fertilizer at about 1965 United States (US) dollars per ton [33]. The total benefit resulting from these scenarios is presented below.

The results indicate huge differences between the six sewage sludge-processing technologies with regards to conversion of energy to economic benefits. Table 5 shows the net energy production conversion to electronic fee for the five cities. According to the electronic fee, the energy benefit could be close to 300 US dollars per year in Osaka. The economic benefit in terms of net energy was not huge

Table 4 Summary of the economic information of five cities in Asia (US dollars)

Item	Osaka	Taipei	Shanghai	Singapore	Bangkok
Electronic fee (MW/h)[a]	8.20	2.72	2.22	6.61	3.42
Carbon tax (ton)[b]	2	5	5	5	5
Phosphate (ton)[c]	1965	1965	1965	1965	1965

References: [a][50], [b][32], [c][19]

for the other cities. However, the continuation of current treatment processes will cost more than 51–1519 US dollars every year and no recovery of P.

The potential costs due to carbon emissions were considered in this study. Table 5 shows the carbon emission tax conversion to electronic fee for the five cities. The conversion of carbon emission to economic benefits indicated large differences between the six sewage sludge-processing technologies across the five cities. In addition to the current state, high-temperature incineration without P recovery process and the cement feedstock scenarios would lead to the highest GHG emissions and result in highest taxes in comparison to the other scenarios. The value of tax used in this study is low. The tax could be higher in cities such as Tokyo and Beijing and, therefore, the carbon emissions would be much higher in these cities.

As shown in Table 6, dry granulation and compost are two scenarios that would cost lower carbon emission fee. The results also indicate that the carbon emission fee could be only about 64 US dollars per year. However, under the current treatment scenario, a cost of more than 8 million US dollars would be incurred every year with no recovery of P. Therefore, these results suggest that the recovery of P is not only an environmental problem but also an economic one.

Although fertilizers are currently not expensive, if the price converse to pure P, the P price still could affect the total economic benefit. P recovery is essential not only from an economic perspective since its natural resources are consistently declining, but also from an environmental point of view since improper disposal of P can pollute soil and water and result in environmental issues such as eutrophication. Table 7 shows the benefits of P recovery for the five Asian cities under six scenarios. Higher P recovery brings greater economic benefits. Thus, in light of the uncertainty, scenario 1 is considered most optimal and provides benefits close to 105,000 US dollars per year. Moreover, although the P ores are not expensive in comparison to other metals, the total P economic benefits from P recovery processes are still huge. Especially in this case, the recovery of P is important not only with regard to environmental impacts but also in the economic sector.

Table 5 Economic benefit in net energy produce in five Asian cities

Scenario		The benefit of energy (US dollars)									
		Osaka		Taipei		Shanghai		Singapore		Bangkok	
		Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
(1)	Compost	311	−301	96	−93	10	−10	134	−129	17	−16
(2)	Cement feedstock	325	−286	100	−88	11	−10	140	−123	17	−15
(3)	Low-temperature carbonization	−320	−932	−98	−286	−11	−31	−138	−400	−17	−50
(4)	Dry granulation	−113	−724	−35	−223	−4	−24	−48	−311	−6	−39
(5)	Pyrolysis gasification	−1430	−2042	−440	−628	−48	−69	−615	−878	−77	−109
(6)	High-temperature incineration	−445	−1057	−137	−325	−15	−35	−191	−454	−24	−57
(0)	High-temperature incineration without phosphorus recovery	−1519	−1519	−467	−467	−51	−51	−653	−653	−81	−81

Scenario 0 means current treatment process. These data were calculated in terms of treatment capacity of 100,000 persons per year

Table 6 Carbon tax fee from six sewage sludge-processing technologies in five Asian cities

Scenario		Carbon tax fee (US dollars)				
		Osaka	Taipei	Shanghai	Singapore	Bangkok
(1)	Compost	7875	18,253	2475	10,522	2533
(2)	Cement feedstock	848,084	1965,699	262,959	1130,585	272,435
(3)	Low-temperature carbonization	10,998	25,491	3410	14,662	3533
(4)	Dry granulation	199	462	62	266	64
(5)	Pyrolysis gasification	13,031	30,203	4040	17,372	4187
(6)	High-temperature incineration	24,598	57,013	7627	32,791	7902
(0)	High-temperature incineration without phosphorus recovery	2889,098	6696,380	895,796	3851,449	928,066

Scenario 0 means current treatment process. These data were calculated in terms of treatment capacity of 100,000 persons per year

Finally, the total benefits are summed in Table 8 which presents the net benefit for the different scenarios. The results suggest scenario 1 as the best program for all cities considered in this research except for Bangkok. The wastewater P percentage was much lower in Bangkok, thus, the economic benefits from P recovery were much lower than in the other cities. But the second treatment method chosen was different between these cities. For example, scenario 4 benefitted Taipei in terms of P recovery and low cost of waste treatment, but for Shanghai city, scenario 6 was optimal. Overall, benefits from P recovery and carbon tax fee were found to be the main factors affecting the result. However, the government should consider the problem and choose the appropriate technology. Regardless of the technology chosen, the environmental impacts and economic benefits for each of the scenarios were better than those for the current state.

Conclusions

The benefits of food waste co-digestion with sewage sludge not only have obviously environmental impact but also provide economic benefits. Three kinds of economic benefit, including energy production, P recovery, and GHG emissions were considered in this study. New energy production is always known to have higher economic values than other benefits. However, due to the likely implementation of carbon tax fee or carbon exchange price in the future, the quality of carbon emissions would play a significant role in determining these costs. The price of fertilizer is known to consistently increase. The benefits from the recovery nutrients, such as, P are not obvious while the economic value from P recovery is relatively low since P fertilizers are not expensive in Asia. However, this research indicates that high-quality P recovered from the treatment processes could be reused as a fertilizer to create high economic benefits. This study also assessed the differences in economic values in different Asian cities.

Therefore, such assessment is needed to highlight the impact of new technologies on the environment as well as the economic sector and to subsequently assist policy formulation. This study examined five main cities in Asia to assess the effects of technology implementation. Furthermore, P recovery percentage and uncertainty in energy production range were determined in this research. This study provided uncertainty range in assessment result, it also could bring policy risk assessment in more deeply.

The final results indicate that the same treatment technology will bring different benefits to different cities. Additionally, benefits from P recovery and carbon tax fee were found to be the two main factors affecting the total economic benefits. Scenario 1 recovered the highest P and had second lowest carbon emissions. Additionally, it could produce energy, thus, this scenario is considered optimal for all Asian cities. The total economic benefits in scenario 5 and scenario 6 were quite similar because the carbon emissions in scenario 6 were higher while the energy benefit in scenario 5 was higher. The P recovery rates for both these scenarios were almost the same, which indicates that the target produce would be the key factor in the choice of technology. Carbon tax fee or carbon exchange price would also be key factors influencing policy formulation. Moreover, energy consumption could also be the key factor in cities experiencing energy shortages.

According to this study, anaerobic digestion technology for treatment of wastewater sludge and food waste could improve the economic value to result not only in energy benefits but also in reduction of carbon emissions and recovery of P. The environmental impact also could be decreased through implementation of policies encouraging P recovery.

Table 7 Economic benefit in phosphorus recovery sector in five Asian cities

Method		The benefit in phosphorus recovery amounts (US dollars)									
		Osaka		Taipei		Shanghai		Singapore		Bangkok	
		Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
(1)	Compost	104,760	93,289	104,760	93,951	127,731	114,551	62,911	56,420	4185	3753
(2)	Cement feedstock	72,415	60,943	67,780	56,971	80,145	66,965	39,760	33,268	2626	2194
(3)	Low-temperature carbonization	72,415	60,943	67,780	56,971	80,145	66,965	39,760	33,268	2626	2194
(4)	Dry granulation	72,415	60,943	67,780	56,971	80,145	66,965	39,760	33,268	2626	2194
(5)	Pyrolysis gasification	93,795	82,324	92,224	81,414	111,599	98,420	55,063	48,571	3656	3225
(6)	High-temperature incineration	100,749	89,278	100,175	89,365	121,831	108,651	60,040	53,549	3992	3560
(0)	High-temperature incineration without phosphorus recovery	0	0	0	0	0	0	0	0	0	0

Scenario 0 means current treatment process. These data were calculated in terms of treatment capacity of 100,000 persons per year

Table 8 Total economic benefit from six sewage sludge-processing technologies in five cities

Method		Total economic benefit (US dollars)									
		Osaka		Taipei		Shanghai		Singapore		Bangkok	
		Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
(1)	Compost	**97,196**	**85,113**	**86,603**	**75,605**	**125,266**	**112,066**	**52,535**	**45,781**	*1668*	*1204*
(2)	Cement feedstock	−775,344	−787,427	−1897,819	−1908,816	−182,804	−196,004	−1090,686	−1097,440	−269,791	−270,256
(3)	Low-temperature carbonization	61,097	49,014	42,191	31,193	76,724	63,523	24,960	18,206	−924	−1389
(4)	Dry granulation	72,103	60,020	*67,283*	*56,286*	80,079	66,879	*39,445*	*32,691*	**2556**	**2091**
(5)	Pyrolysis gasification	*79,334*	*67,251*	61,581	50,583	107,511	94,311	37,076	30,321	−607	−1071
(6)	High-temperature incineration	75,706	63,623	43,025	32,027	*114,189*	*100,988*	27,058	20,303	−3934	−4398
(0)	High-temperature incineration without phosphorus recovery	−2890,616	−2890,616	−6696,847	−6696,847	−895,847	−895,847	−3852,102	−3852,102	−928,147	−928,147

Scenario 0 means current treatment process. These data were calculated in terms of treatment capacity of 100,000 persons per year

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