Bioenergy Potential Assessment of Wastewater Sludge and Forestry Waste in Taiwan: Financial Analysis and Life Cycle Assessment

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Abstract

Final disposal of enormous wastewater sludge in Taiwan becomes an environmental issue since most landfill sites will be closed in the next decade. The low heat value and high ash content of sludge restrict its energy application using thermochemical processes. Co-firing of sludge with the abundant forestry wastes like wood chips in Taiwan seems a feasible alternative. The heat value of mixture can be elevated accordingly. The existence of woody materials mitigates the typical operation problems like sand sintering and clogging in commercial fluidized reactors due to the sludge ashes.

This study conducts the financial analysis and life cycle assessment of the co-firing process, pyrolysis and gasification, based on the running data in a commercial cogeneration power plant in Taichung (central Taiwan), along with the pilot-scale tests of pyrolysis (at 500^{o}C) and gasification (at 800^{o}C). In the scenario, the sludge and wood chips are conveyed from one wastewater treatment plant in Taichung and an experimental forest in Nantou, respectively, to the cogeneration power plant. The results show that among the three processes, the conventional co-firing in the cogeneration power plant is the most economically feasible, though the environmental impacts are highest, mainly from the aspects of greenhouse effects and acid rain. The pyrolysis costs less than the gasification, and the derived environmental impacts are also fewer than gasification.

Keyword: Biomass; sugi; sludge; pelleting; gasification; pyrolysis; SimaPro; environmental impacts; ash in the sludge

1. Introduction

Converting biomass to bioenergy can decrease the dependence on fossil fuels. Also the bioenergy is nearly "carbon neutral" and emit less greenhouse gas (GHG) into the atmosphere. Vascular plants can build up carbohydrate from carbon dioxide and water in the presence of sunlight and in the process absorbing energy through the photosynthesis—carbon fixation (Figure 1). The relevant technologies are categorized into: (1) physical processes; (2) thermo-chemical processes; and (3) biological processes. Thermochemical ways are more mature than biochemical ways. The most widely applied procedure is the direct combustion of biomass, or co-firing with coals, a thermochemical converting technology. Moreover, both gasification and pyrolysis are considered as potential opportunities for recovering valuable material and energy from waste. Gasification can convert biomass into syngas, where pyrolysis converts them into liquid biofuel. The advantages of gasification and pyrolysis for greater flexibility in terms of energy production and material recycling remain evident, though the pretreating requirement may be more stringent [1-3]. Dewatering and drying are the most essential pretreatment to reduce the moisture content. Usually crushing, milling and pelleting are necessary to save the energy consumption of logistics.

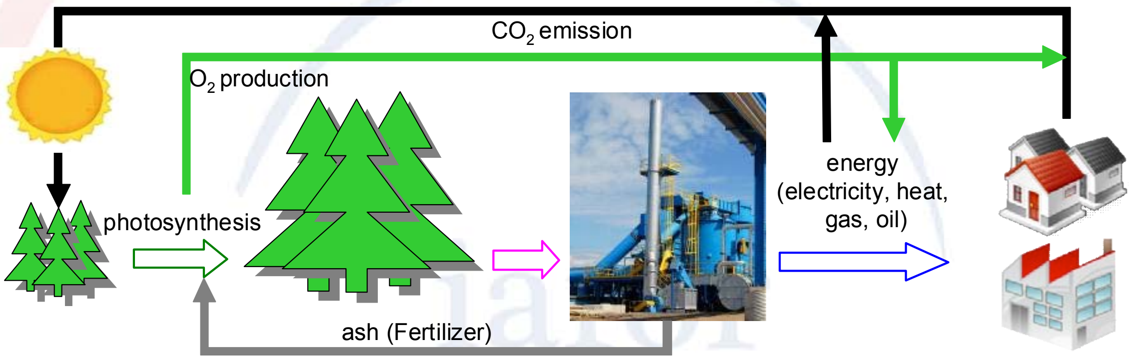

Figure 1 Carbon neutral characteristics of biofuels from vascular plants

On the other hands, final disposal of enormous wastewater sludge in Taiwan becomes an environmental issue. Since most landfill sites will be closed in the next decade, the dewatered sludge may soon face the dilemma that there is nowhere to go. According to our estimation, sludge for disposal will increase up to 2,000 tons per day after year 2030 in Taiwan while the total sewage is 6 million cubic meters per day (Figure 2).

Using sewage sludge as a biofuel could be feasible using the currently commenced incinerators. Other alternatives, like pyrolysis and gasification, are also possible, though the technology is not mature (Figure 3). However, due to the low connection of domestic sewage of households in Taiwan, the organics in the influent of wastewater treatment plants are generally insufficient. It leads to the low heat value in the sludge, as well as the high ash content in sludge (Table 1). It also restricts the energy application using thermochemical processes of sludge. In Taiwan, most applied resource utilization of sludge is for the raw materials of "construction materials", though the organics in the sludge also raise some other problems in application. Figure 4 depicts a typical decision-making protocol in Taiwan for sludge resource utilization.

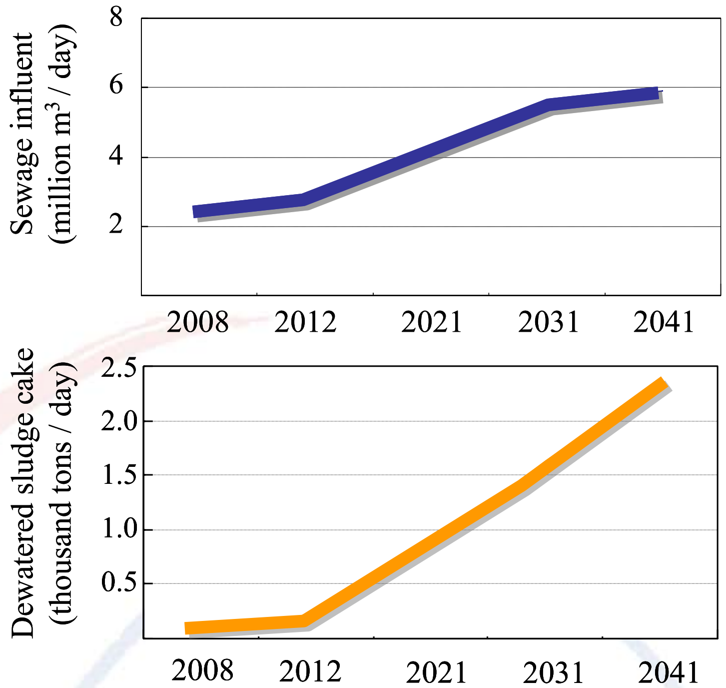

Figure 2 The estimated growth of sewage and sludge in Taiwan

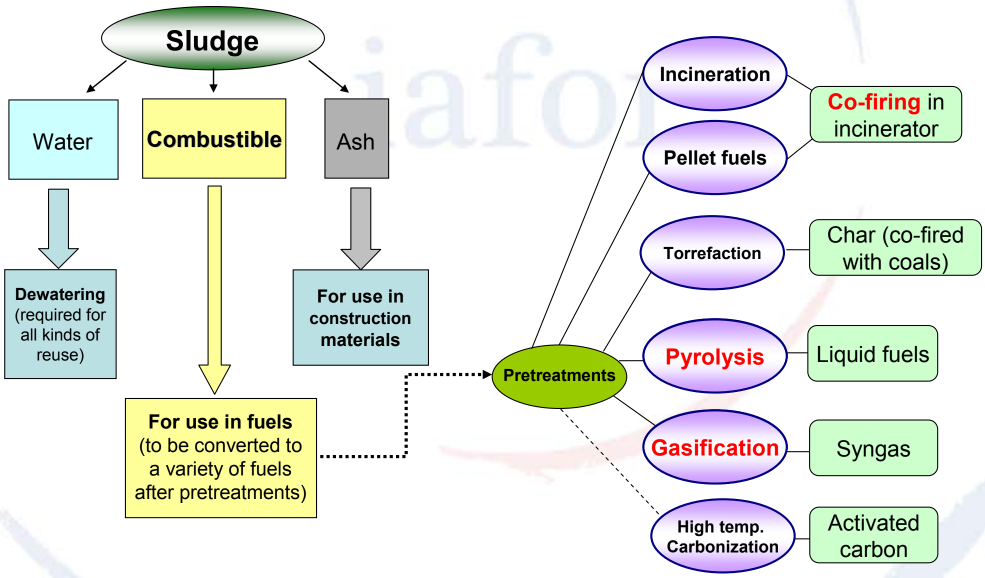

Figure 3 The possible energy application of sludge

Table 1 Thermal properties and composition of sludge in Taiwan

Items	Typical measured values in Taiwan	
Composition of sludge after drying	Moisture: 4.7~8.5 % Combustibles: 41.6~60.0 % Ash: 31.5~53.7%	
Low-level heating value	1,600~3,700 kcal / kg	
Elemental composition	C: 27.5 %	H: 4.4 %
	N: 3.45 %	S: 0.6 %
	Na: 417 mg / kg	K: 2,421 mg / kg
	Ca: 3,418 mg / kg	Mg: 1,075 mg / kg
	Si: 442 mg / kg	P: 11,148 mg / kg
	Fe: 10,926 mg / kg	Mn: 2,399 mg / kg
	Cu: 527 mg / kg	Al: 16,068 mg / kg

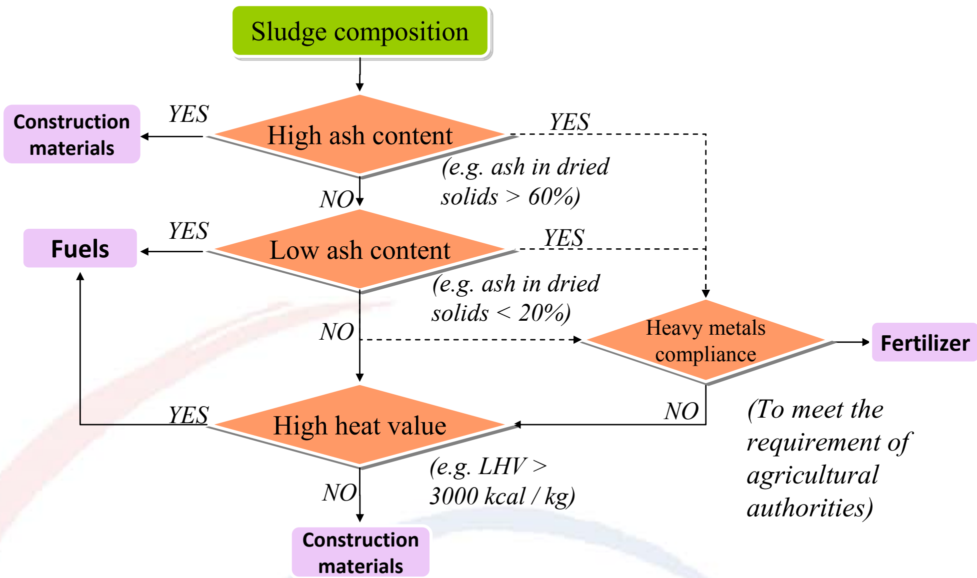

Figure 4 The decision making protocol of sludge resource utilization

2. Scenario Description: Co-treatment of sludge and forestry waste

To solve the aforementioned restriction of sludge treatment, a feasible alternative is to treat the sludge with the abundant forestry wastes like wood chips in Taiwan. The heat value of mixture can be elevated accordingly. The existence of woody materials mitigates the typical operation problems like sand sintering and clogging in commercial fluidized reactors due to the sludge ashes. The scenario for the subsequent evaluation is that the sludge and wood chips (forestry waste) are conveyed from one wastewater treatment plant in Taichung and an experimental forest in Nantou, respectively (Figure 5). Taichung is the largest city in central Taiwan, while Nantou is a famous forestry county. The sludge and forestry waste are then conveyed to the cogeneration power plant in Taichung harbor (powering capacity 5,824 MW). Based on this concept, not only the forestry waste, but also other agricultural waste, including the biomass from the constructed wetlands, may be co-treated with the sewage sludge (Figure 6).

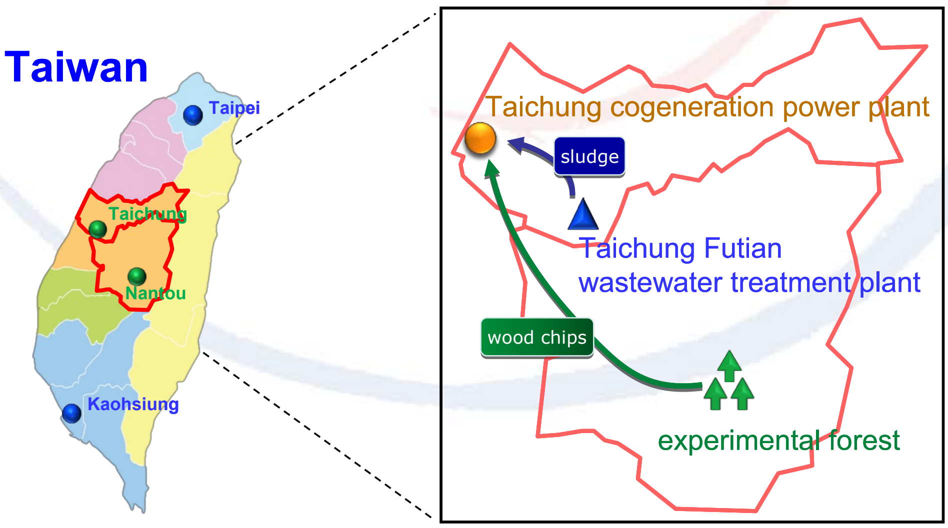

Figure 5 The scenario for subsequent description

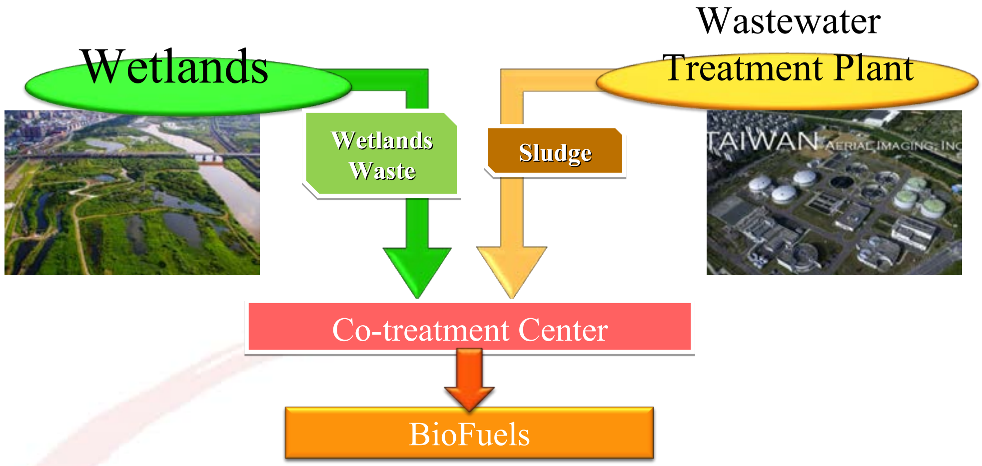

Figure 6 A future prospect: Co-treatment of wetland biomass and sewage sludge

To evaluate the feasibility, we have conducted a survey on the pelleting, pyrolysis and gasification of woody materials as well as its mixture with the sludge cake from municipal wastewater treatment plant. This study conducts the financial analysis and life cycle assessment of the co-firing process, pyrolysis and gasification, based on the running data in a commercial cogeneration power plant in Taichung (central Taiwan), along with the pilot-scale tests of pyrolysis (at 500^{o}C) and gasification (at 800^{o}C). All the tests are performed in pilot scale. The performance was evaluated, and the corresponding environmental impacts were also assessed using SimaPro 7.1 to compare with using coals, especially on the aspects of ecosystem damage and human health risk.

For the financial assessment, the cost and environmental impacts from the major stages of this process are considered, including dewatering, pelleting, logistics, furnace operation, derived pollution control (wastewater and flue gas) and product application. To evaluate the possible impacts of using bioenergy in relative to using fossil fuels, life cycle analysis (LCA) is a method to summarize the environmental aspects and potential effects throughout a product's life cycle starting from raw material acquisition, manufacture, use, recycling and disposal. It is helpful in measuring the ecological aspects of products composed of different raw materials though used for the same purposes. When selecting environmentally friendly fuels, raw materials, products, and production processes, the results of a comparative LCA study provide reference value for decision makers [4,5]. SimaPro 7.1 was widely used in this field for evaluating environmental impacts and damage of inventory elements. It provides seventeen methods for evaluation on various aspects, especially the greenhouse effects, eutrophication, acid rains, and so on.

3. Experimental

3.1 Biomass materials

Sugi (*Cryptomeria Japonica*) and sewage sludge cake taken from Futian Wastewater Treatment Plant in Taichung, Taiwan are tested in this study. Sugi was taken from the experimental forest of National Taiwan University at Nantou, Taiwan. The materials was first crushed and milled into size less than 1 mm for subsequent tests. The sludge cake was originated from the primary and secondary sludge in Futian Wastewater Treatment Plant. The sludge was thickened, anaerobically digested, dewatered and air dried to reduce the moisture content less than 40% (w/w).

3.2 Biomass pelleting

In this study, the ring-die extrusion molding machine (also known as "ring-die molding") was applied to pelletize the sugi and sludge to form pellets. The appearance of this machine (Yong-Ming YMHP-15) is illustrated in Figures 7. The maximum pelleting capacity is 20 kg per hour with the rotating speed 350 rpm. It provides two different mold sizes (6 mm and 8mm), where we selected 6-mm mold in this test. To soft the lignin, the system may heat up the raw materials, and the maximum temperature is controlled using the water cooling. The dried sewage sludge was blended with smashed sugi for pelleting the "mixed pellets" (Figure 8). After repeated tests, the optimal temperature for pelletizing is around 80 ~ 90^{o}C. The key factor to perform good pellets is to keep a homogeneous "roller press layer" in the mold, so that it prevent cracks appearing on the pellet surface. The pellets of sugi, sludge and the mixture are shown in Figures 9.

(a) The machine

(b) Ring-die mold

(c) Inside the ring-die mold

(d) scraper

(e) Feeding process

(f) Inside the mold filled with raw materials

(g) Ring-die mold clogged with raw materilas

(h) Pellet coming out from the ring-mold

Figure 7 The appearance of ring-die molding machine (Yong-Ming YMHP-15)

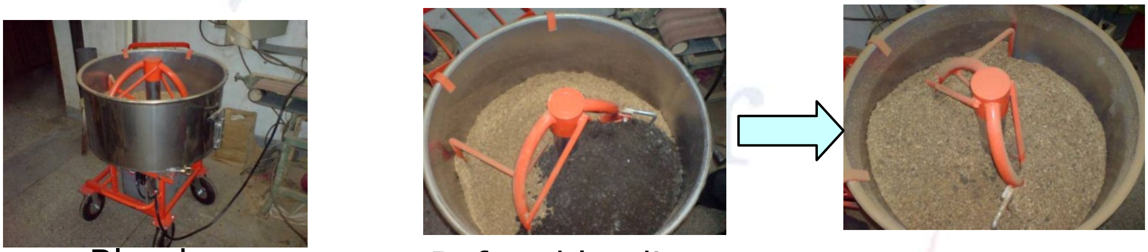

Figure 8 The blending of sludge and woody chips (sugi)

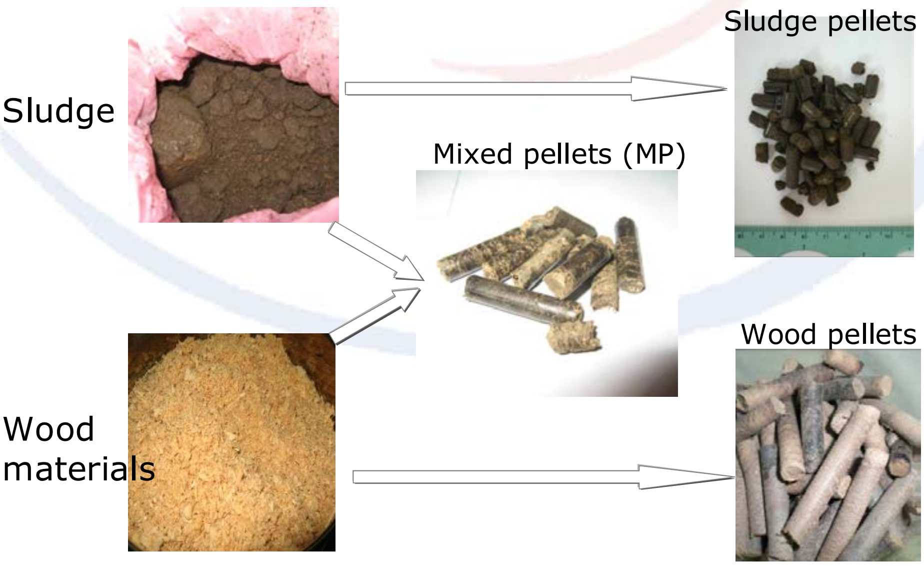

Figure 9 The appearances of sugi, sludge and their pellets

3.3 Pilot-scale pyrolyzer

The pilot-scale pyrolyzer and gasifier were used to conduct the pyrolysis and gasification in this study. The bubbling fluidized bed pyrolyzer included the purge gas system, heating facility, carbon removal, cyclone, and water-cooling system (Figure 10). For the convenience of disassembling, all related pipelines were connected by flange, and the pilot plant was fixed on a steel frame. Pyrolysis testing of the sugi, sludge, and their mixed pellets (the ratio of sugi to sludge is 50:50) was conducted in a pilot-scale pyrolyzer with the maximum feedstock rate of 5 kg/hr. Based on the calculation, the minimum fluidized velocity (Umf) of sand bed is 19 cm/s. During the test, the velocity of the purge gas varied from 2Umf to 4Umf to observe the effects on the conversion rate (produced oil/feedstock×100%). It is noticed that setting purge gas velocity at 2Umf could reach a maximum conversion.

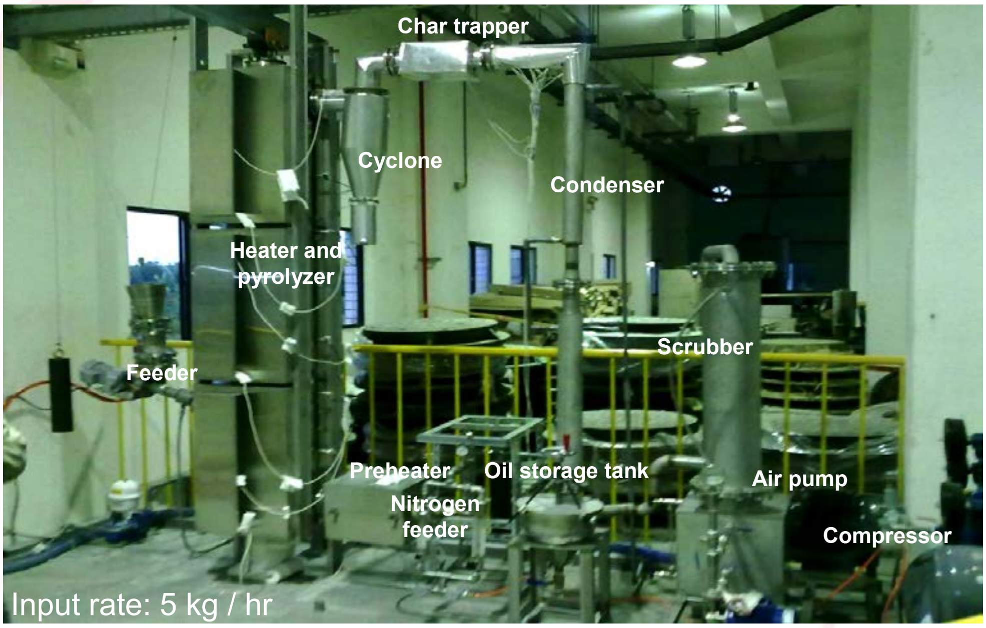

Figure 10 Pilot-scale pyrolyzer

3.4 Pilot-scale gasifier

Gasification testing of the sugi, sludge and their mixed pellets was conducted in a pilot-scale gasifier with the maximum feedstock rate of 5 kg/hr (30 kWth), diameter of 7.6 cm, and height of 1.9 m. The main components include feeder, gasifier, tar sampling, cyclone and scrubber (Figure 11). The testing variables included the gasification temperature (700 and 800°C), the air equivalence ratio (ER, 0.2, 0.3 and 0.4), and the steam injection. The feedstock rate depended on the ER values.

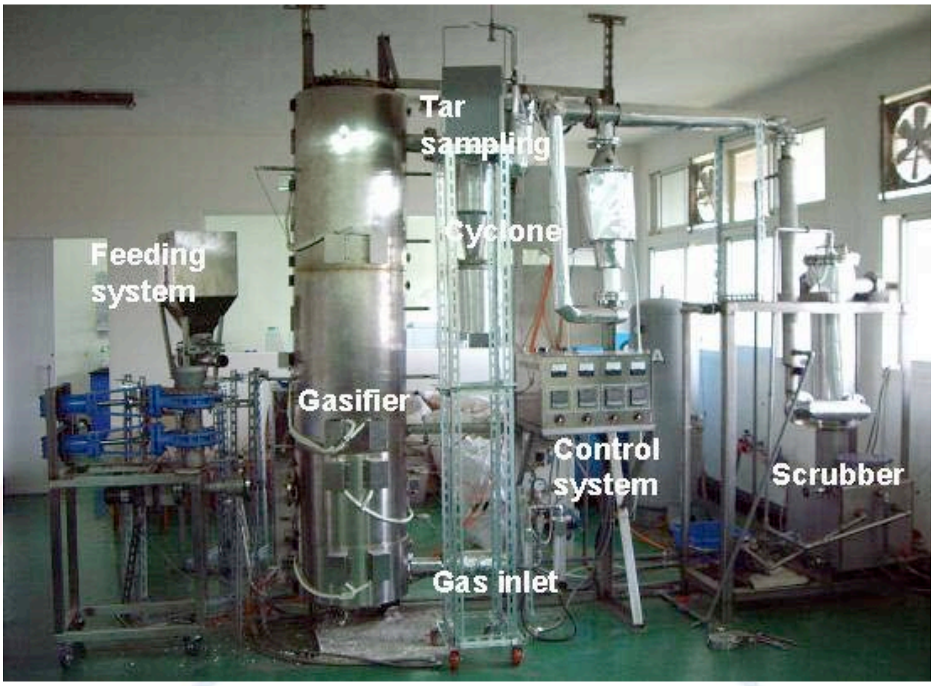

Figure 11 Pilot-scale gasifier

3.5 Environmental impact assessment

The LCA software SimaPro 7.1 applying Eco-indicator 95 as evaluating method was used to evaluate the environmental impacts and damage of inventory elements. The Registration Code of SimaPro 7.1 used in this study is K8PB PX8M 2L5N WY73. The Eco-indicator 95 method has been published in 1994 by a team of experts mainly from the Dutch PRé consultant and implemented over decade and based on European activities in 1990. It is a weighting method for the assessment of environmental impact that damages ecosystems or human health on a European scale and can fulfill the requirements of product design for environment. The structure of the Eco-indicator weighting method is schematically represented in Figure 12 [6].

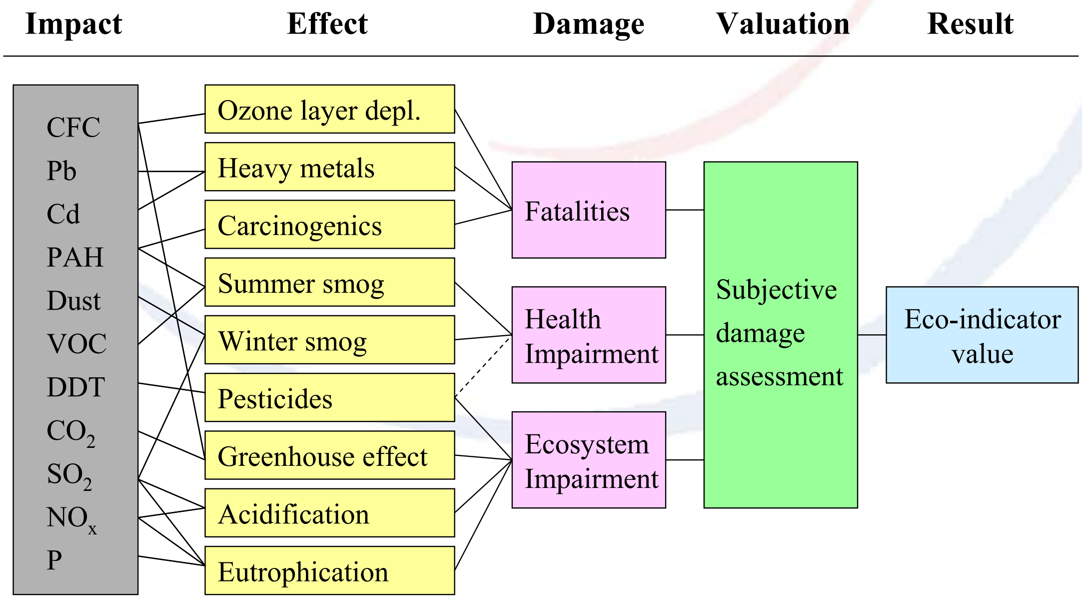

Figure 12 Schematic representation of the Eco-indicator weighting method

4. Results and discussion

4.1 Pelleting characteristics of sugi and sewage sludge cake

The properties of the raw materials and pellets were listed in Table 2 to reveal the difference before and after pelleting. After pelleting, the bulk density of woody plant increases about four times, from 144 kg/m^3 to 562 kg/m^3. For sludge, there was no obvious change on bulk density. The pellet durability index (PDI) was determined followed the method ASAE S269.3 [7], to evaluate the durability of pellets during the logistics. PDI of sludge is 91.2% and is higher than that of sugi (83.1%), implying the sludge pellets can resist the stress during transportation. The woody pellets, On the other hand, are more easily crushed. As pelleting is a kind of physical process, three-components (water, combustibles and ash), lower heating value (LHV) has no noticeable change after pelletizing. The water content dropped slightly after pelleting and increased the combustibles accordingly. The element component also has no obvious change except hydrogen. Hydrogen lowers after pelletizing because the water content decreases.

For the mixed pellets (sugi : sludge = 1:1), noticeably some properties are not located between those of sugi and sewage sludge. PDI of the mixed pellets is lower than sugi and sewage sludge. It implies that the surface hydrophilicity of sugi and sludge differs significantly, and the two materials could not be bound tightly in the pellets. Similarly LHV of the mixed pellets is 3,858 kcal/kg, higher than the average of LHV's of sugi and sludge (3,470 kcal/kg). A possible explanation is the inhomogeneity of the mixture and lead to the inaccuracy of LHV measurement.

Table 2 The comparison of biochemical characteristics of various biomass before pelletizing and after being pelletized

Parameters	Biomass	Sugi (*Cryptomeria japonica*)	Sewage sludge	Mixed pellets
Bulk density (kg/m^3)	Raw materials	144	581	-
	Pellets	562	577	577
Pellet Durability Index (PDI) (%)	Raw materials	-	-	-
	Pellets	83.1	91.2	76.0
Water (%)	Raw materials	12.0	21.3	-
	Pellets	10.1	10.8	10.8
Combustibles (%)	Raw materials	87.4	43.8	-
	Pellets	89.1	46.8	67.3
Ash (%)	Raw materials	0.59	34.9	-
	Pellets	0.85	42.4	21.9
Lower Heating Value (LHV) (kcal/kg)	Raw materials	4,470	2,629	-
	Pellets	4,285	2,654	3,858
Carbon (%)	Raw materials	45.5	27.5	-
	Pellets	49.7	25.1	36.9
Hydrogen (%)	Raw materials	6.11	4.37	-
	Pellets	6.92	2.91	4.43
Nitrogen (%)	Raw materials	0.07	3.45	-
	Pellets	0.14	4.14	3.52
Sulfide (%)	Raw materials	0.05	1.28	-
	Pellets	0.05	1.45	0.75
Oxygen (%)	Raw materials	48.3	63.2	-
	Pellets	43.2	66.4	54.4

Note: Mixed pellet: The dried sewage sludge was blended with smashed sugi

4.2 Pyrolysis and gasification testing

To determine the optimal parameters, we have examined the effect of pyrolysis temperature (400, 500 and 600°C) on the conversion rate at feedstock rate at 2.2 kg/hr. The results revealed that the conversion rate of three materials (sugi, sludge and their mixed pellets) have the similar tendency which ascended at first and descended at last. The optimal temperature with the highest conversion rate of pyrolysis is 500°C, where the conversion is 34% for sugi, 12% for sludge, and 20% for mixed pellets (Table 3). Apparently the biomass cannot be efficiently decomposed at 400°C, while it can be easily decomposed into smaller molecules at 600°C and not condensed as oil.

Among the three materials, sludge had the lowest carbon content and the highest ash content. The high ash content in the sludge resulted in the sintering between fluidized sands and the ash and may cause defluidization. The sands became lump-like material, and this increased the difficulty in maintenance. On the other hand, woods had higher carbon and less ash, and the conversion could reach between 25-35%. The mixed pellets, however, performed between the sludge and the wood. The sintering problems of sands caused by ash in the sludge were also mitigated and thus elevated the conversion.

Noticeably, compared with the conversion (around 50%) reported in the literature, the conversion in this pilot plant was low, possibly because of the insufficient length of the cooling system, which could not condense all the oil in the flow gas. In the test, the operator kept a lower purge gas flow rate (2Umf) to ensure more oil being condensed. Such a system is different from so-called "flash pyrolysis". Extending the cooling length and increasing the cooling water flow circulation may be the first priority to improve the system.

For gasification tests, more detailed results were reported in Wu et al. [8]. As the value of ER increased, concentration of three fuel gas (CO, H_2 and CH_4) increased accordingly. On the other hands, higher gasifying temperature led to more fuel gas (syngas CO and H_2). Thus the optimal condition was determined as gasifying temperature at 800°C and ER at 0.3. Feedstock rate in this case is 3 kg/hr. Table 3 also listed the composition of gasifying products. Though some data scattering exists, the hydrogen concentration reaches maximum (25%) in the case of mixed pellets, where the concentration of CO exhibits the similar trend. Possibly alkali metals contained in the ash of sludge might function as some kind of catalyst to facilitate the conversion the hydrocarbon to hydrogen and carbon monoxide, instead of converting to tar. It may function similar like commonly used catalyst dolomite $CaMg(CO_3)_2$. This is different from what we observed in pyrolysis, where ash in the sludge did not facilitate the conversion of mixed pellets.

Similar to the case in pyrolysis, ash in the sludge caused sintering with the sands in gasifier and would lead to the non-fluidizable bed. Using sludge as the only raw materials would be difficult to operate and control as defluidization may occur unexpectedly. Sugi and the mixed pellets may be easier for conducting the gasification.

Table 3 Performance of pilot-scale testing of pyrolysis and gasification

Performance / Biomass	Pyrolysis	Gasification			
	Oil conversion	CH_4	H_2	CO_2	CO
Sugi	34%	9	21	31	28
Mixed pellets (50% sugi + 50% sludge)	12%	9	25	30	32
Sludge	20%	15	17	32	26

4.3 Cost analysis of sludge disposal as fuels

Co-firing (combustion) of mixed pellets is now commercially available in Taiwan for power generation. The typical cost is NT$2/kWh (7 US cents/kWh) for the power generation using biomass. On the other hand, gasification and pyrolysis of biomass are not so common in Taiwan. The following cost information is based on the operation in United States, and is then adjusted according to the pilot testing of this study. In summary, typical cost using gasification is NT$9/kWh (30 US cents/kWh). Typical cost using pyrolysis is around NT$12/kWh (40 US cents/kWh), which is rarely reported in literature because the pyrolysis oil is not suitable for power generation.

4.4 Environmental impacts

To evaluate the possible effects on environment when using the biogas, four scenarios of production steam were compared as listed in Table 4. "Base" is the coal combustion in a entrained bed reactor. "Case A" is the gasification on the bubbling-fluidized bed using the pellets of woody waste to produce Syngas. Afterward, the syngas is combusted with coals to produce steam. "Case B" is the same as Case A while $Ca(OH)_2$ is added in the reactor as catalyst. "Case C" is the pyrolysis on the bubbling-fluidized bed using the pellets of woody waste to produce liquid biofuel, and then combusts with fuel oil to produce steam. The input data refer to the literatures [8,9] and the results from the aforementioned pilot-scale testing. The comparison of environmental impacts for four scenarios using Eco-indicator 95 in SimaPro 7.1 is illustrated in Figure 13.

Table 4 Four steam producing **scenarios**

Scenario	Process	Materials	Product
Base	Combustion	Coal	Steam
Case A	1. Gasification	Woody waste	Syngas
	2. Combustion	Syngas +coal	Steam
Case B	1. Gasification with $Ca(OH)_2$ injection	Woody waste	Syngas
	2. Combustion	Syngas + coal	Steam
Case C	1. Pyrolysis	Woody waste	Pyrolysis oil
	2. Combustion	Liquid biofuel + fuel oil	Steam

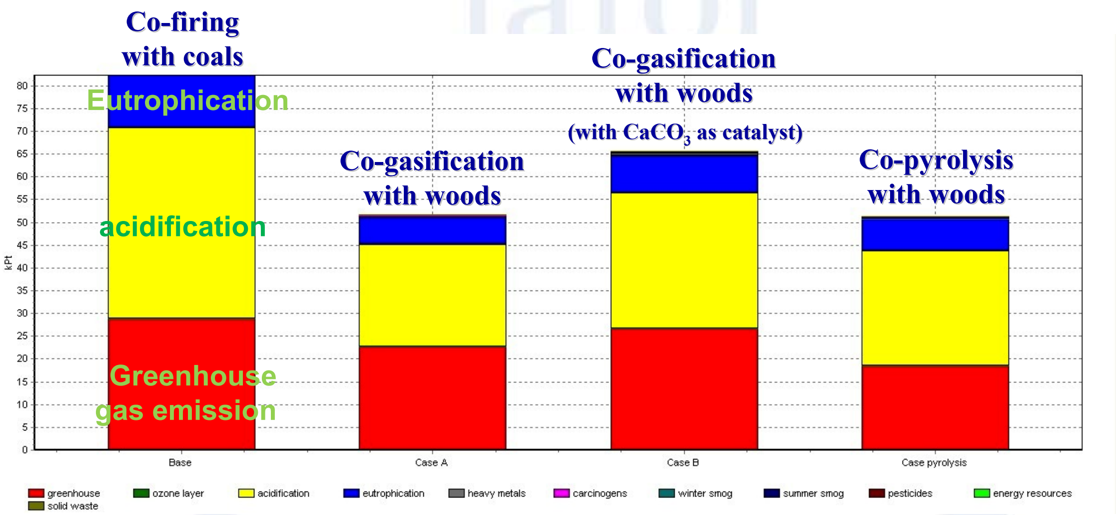

Figure 13 The comparison of four steam producing projects using Eco-indicator 95

The results are revealed that the coal combustion (Base) led to the most significant environmental impacts, followed by Case B, Case A, and Case C. The main impacts included greenhouse effects, acidification and eutrophication. The evaluation result may be ascribed to the noticeable emission of CO_2 and NO_x in the scenario "Base". The other three cases using woody waste may be considered as more "carbon neutral", while the emission of NO_x was low in the biomass that could be ignored. Thus it gives fewer impacts than using fossil fuels. As operated in lower temperature, pyrolysis may release less carbon dioxide, and it led to the lowest environmental impacts. More studies are required to give more objective evaluation.

4. Conclusions

The results show that municipal sludge in Taiwan is not suitable for being utilized as fuels alone. Co-treatment with forestry wastes (like wood materials) is feasible and mitigates the problems like ash melting and low heat value. We have evaluated the performance of pelleting, pyrolysis and gasification of sugi and its mixture with sewage sludge. Noticeably, the addition of sludge may play different roles in the individual process. When adding sludge to form the mixed pellets, the pellet durability index of mixed sludge became worse than the two raw materials. The possible explanation is their different surface hydrophilicity leads to the binding less efficient. More sludge in either pyrolysis or gasification would lead to more defluidization and sand sintering. For pyrolysis, the conversion became worse when the portion of sludge increased. At the optimal temperature 500^{o}C, the conversion kept dropping from 34% to 12% when more sludge is added. On the other hand, for gasification, the syngas (hydrogen and carbon monoxide) concentration at the optimized criteria (ER = 0.3 and gasifying temperature 800^{o}C) reaches maximum in the case of mixed pellets. Ash in sludge may play an important role to catalyze the hydrocarbon decomposition in this case. The environmental impacts analysis showed that both gasification and pyrolysis gave fewer impacts, where pyrolysis may have the lowest impacts among the four scenarios. Biomass pyrolysis and gasification, which produce oil and syngas respectively, may further increase the energy efficiency and mitigate the environmental impacts compared to the combustion or co-firing. In summary, among the three processes, the conventional co-firing in the cogeneration power plant is the most economically feasible, though the environmental impacts are highest, mainly from the aspects of greenhouse effects and acidification. More studies are still required to evaluate the feasibility of these thermal chemical processes for sludge resource utilization.

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