

# Characteristics of Emissions from Reclamation of Solid-recovered Fuel (SRF) in a Cogeneration Plant

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## ABSTRACT

The feasibility of the replacement of coal with solid-recovered fuel (SRF) transformed from waste lubricants was investigated in this work. In addition, the emission characteristics of SRF reclamation in a cogeneration plant were evaluated. The raw waste lubricants collected from a factory that manufactures tinplate cans were pretreated, mixed with wood dust, bentonite, and coal ash, and then remolded into pellet SRF. The coal and remolded SRF were reclaimed in a cogeneration plant. The reclamation performance of the tested fuels was evaluated by analyzing the pollutant characteristics of the bottom ash, fly ash, and flue gas. The PCDD/F concentrations in the flue gas in the runs without coal (0.003 ng I-TEQ Nm<sup>-3</sup>) were slightly lower than those in the runs with coal (0.102 ng I-TEQ Nm<sup>-3</sup>). According to the monitoring data for CO, O<sub>2</sub>, NO<sub>x</sub> and combustion efficiency, the substitution of SRF for coal improved the combustion conditions. The results showed that transformation of waste lubricant into SRF for reclamation is a promising method by which to take both waste treatment and energy regeneration into consideration.

**Keywords:** Combustion efficiency, Ash, SRF, Wood dust, Coal

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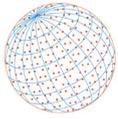
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## 1 INTRODUCTION

Due to rapid industrial development, the amount of waste being generated has increased dramatically in the last few decades. It is an important issue to dispose of this waste properly. For this reason, the priorities for waste treatment, as imposed by European strategies for waste management, include prevention, reuse, recycling, recovery of energy or resources, and disposal, in that order (Directive 2008/98/EC). Following these strategies, technological development for energy recovery from waste has flourished for the last few decades (Chang *et al.*, 1999). Among these available technologies, the combustion process, typically called incineration, is the most common technology used to convert bio-waste into energy (Lombardi *et al.*, 2015).

Bio-waste is usually incinerated to generate steam and then transformed into electricity via a cogeneration system or directly used in industrial processes (Vermeulen *et al.*, 2011; Murer *et al.*, 2011). Incineration is applied to dispose of various types of materials, including organic liquid waste, municipal solid waste, organic sludge, refuse-derived fuels (RDFs), and even unsorted residual waste (Arena, 2012; Myrin *et al.*, 2014; Leme *et al.*, 2014). In addition, incineration is an efficient technology that can be used to convert waste into energy and thus has several advantages. In general, it dramatically reduces the mass of waste by approximately 70 to 80% and the volume by approximately 80 to 90% and thus increases the service life of landfills (Consonni *et al.*, 2005). It can also destroy organic pollutants and reduce greenhouse gas emissions more than anaerobic decomposition processes (Buekens and Cen, 2011; Psomopoulos *et al.*, 2009). According to a life



cycle analysis, incineration can also lighten environmental burdens because of the conversion of bio-waste into energy (Arena *et al.*, 2003; Azapagic *et al.*, 2004).

The RDF production process converts waste into fuel and makes it possible to acquire energy elsewhere. The solid waste is pretreated, mixed, and remolded into RDF in the form of pellets or short cylinders (Nasrullah *et al.*, 2015) and can be transported to an RDF reclamation plant to generate energy or steam (Gug *et al.*, 2015; Zhou *et al.*, 2013). Because this is a flexible and convenient way to convert waste into energy, RDF reclamation through incineration has drawn worldwide attention and also is now regarded as a promising waste-to-energy technology that has been applied in the last decade (Rada and Andreottola, 2012). However, persistent organic pollutants, such as PCDD/Fs (polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans), are unavoidably generated during the incineration process (Nam-Chol and Kim, 2017; Qiu *et al.*, 2020), and these pollutants affect public health; for example, they can further have impacts on the eyes (Chang *et al.*, 2020). The flue gas emitted from this process also requires proper disposal to prevent release into the ambient air. Therefore, it is essential to investigate the pollutant characteristics of the RDF reclamation process.

In the manufacturing of tinplate cans, a cutting oil, mainly composed of palm oil, often serves as a lubricant between the cutting tools and the tinplate. In addition to lubrication, the cutting oil also dissipates the heat generated during the cutting process so as to protect the cutting tools. After operating for a period of time, the lubricant gradually degrades and must be renewed. The waste lubricant has high heating value and thus is suitable for recycling as a fuel. However, in addition to palm oil and the original additives, the waste cutting oil still has water, metal scraps, and impurities that must be removed before transforming the waste lubricant into RDF.

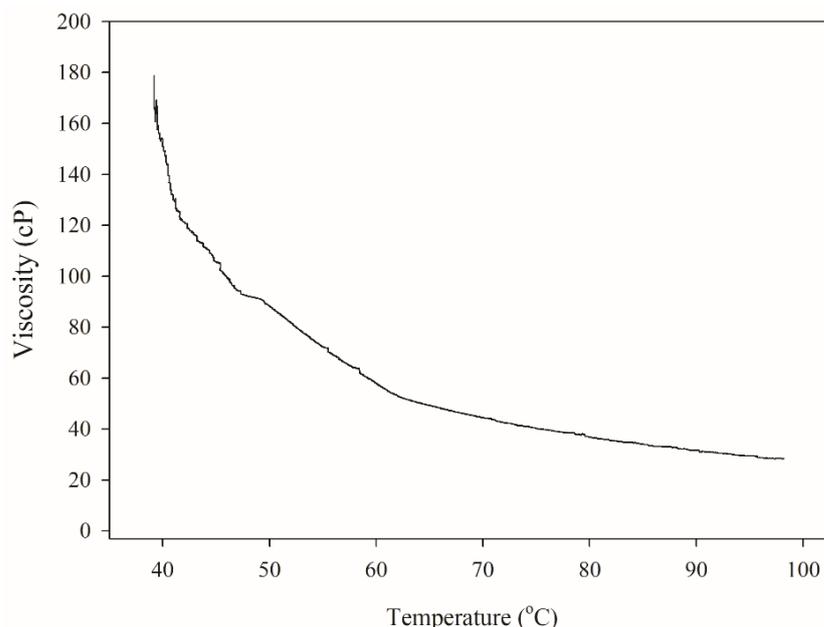
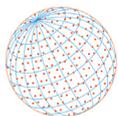
Recently, wastes have often been regarded as dislocated resources, and, therefore, RDF is also called solid recovered fuel (SRF). In this study, a waste lubricant collected from a canned-food factory was pretreated, mixed with additives, and remolded into SRF. The characteristics of pollutants generated during the reclamation of SRF in a steam generation plant were investigated. In addition, the feasibility of replacement of coal with SRF was also evaluated.

## 2 MATERIALS AND METHODS

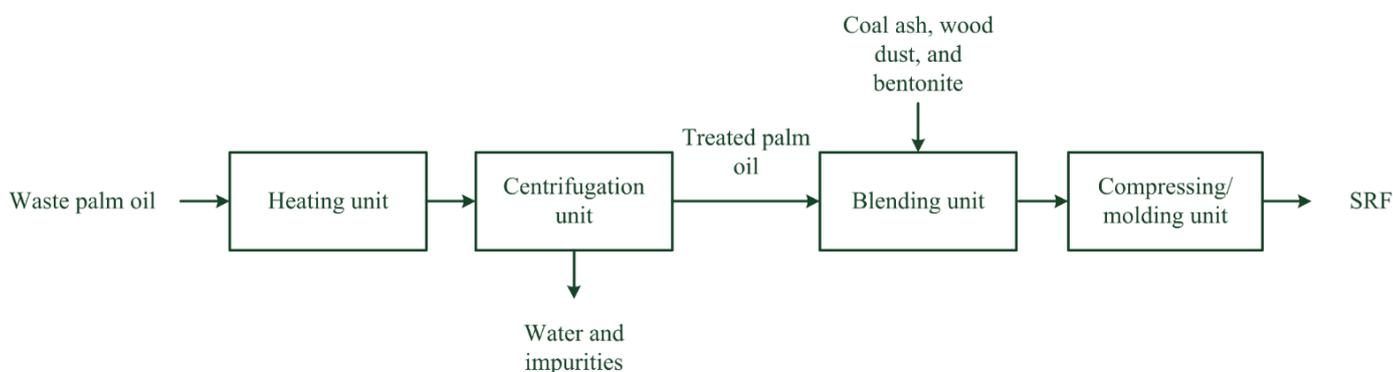
### 2.1 Pretreatment of Waste Lubricant and Preparation of SRF

The waste lubricant under consideration was collected from a canned-food factory in Tainan City, Taiwan. The waste lubricant was abandoned from a production line for manufacturing of tin cans and temporarily stored in 55-gallon oil drums in the plant. These drums were transported to Shi-Chang Co., Ltd. for further disposal. The waste lubricant was in a semi-solid state at room temperature and had to be heated to separate the impurities. The viscosity of the waste lubricant at different temperatures was measured via a viscometer (Brookfield, DV2T) to obtain the appropriate heating temperature for the separation process. Fig. 1 shows the viscosity of the waste lubricant at different temperatures. At room temperature, the waste lubricant was a semi-solid ointment-like substance. When the waste lubricant was heated to 40°C, it began to melt, and its viscosity was reduced to 180 cP. The viscosity of the waste lubricant was further reduced to about 40 cP at 80°C, and it was possible to dispose of the waste lubricant above this temperature. Fig. 2 shows flow chart of the SRF manufacturing process. The waste lubricant was heated to approximately 90°C to reduce its viscosity. Then, the melted waste lubricant was revolved at a rotation speed of 12,000 rpm via centrifugation to remove the water content, metal scraps, and impurities.

Table 1 shows the properties of the raw and treated waste lubricants. The original waste lubricant comprised 24.6% water and 72.4% combustible content. The main composition of the combustible content was C (56.7%), H (7.74%), and O (7.27%), and the low heating value of the raw waste lubricant was 6,940 kcal kg<sup>-1</sup>. After the treatments, the combustible content increased to 88.2% and was mainly composed of C (77.1%), H (4.69%), and O (6.22%). The water content in the treated waste lubricant was reduced to 8.6%, and, thus, its low heating value increased to 8,690 kcal kg<sup>-1</sup>. Most of the metals were removed from the waste lubricant, and the levels of anthropogenic metals, including Cd, Cr, Cu, Mn, Ni, Pb, and Zn, were all reduced to less than 500 mg kg<sup>-1</sup>.



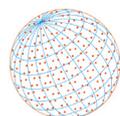
**Fig. 1.** Viscosity of waste palm oil versus different temperatures.



**Fig. 2.** Process for transformation of waste palm oil into SRF.

Before being cooled down, the treated waste lubricant was blended with wood dust, coal ash, and bentonite. The properties of SRF additive are shown in Table 2. The wood dust was 88.4% combustible content, and the metals were all in trace amounts. It had a low heating value of  $3,300 \text{ kcal kg}^{-1}$ , which played a role to adjust the heating value. The levels of Cl and S in the wood dust were  $2,650$  and  $6,810 \text{ mg kg}^{-1}$ , respectively, which probably came from the paint on the original waste wood. The coal ash had a 90.2% ash content, which was used to improve the physical strength of the SRF. Bentonite, mainly composed of montmorillonite, is an absorbent aluminum phyllosilicate clay. Except for Si, bentonite is mainly composed of Al ( $13,900 \text{ mg kg}^{-1}$ ), Ca ( $23,300 \text{ mg kg}^{-1}$ ), and Fe ( $26,500 \text{ mg kg}^{-1}$ ), which are all crust metals. The bentonite expanded and became adhesive when it was mixed with water, and thus, it served as a binder for the mixture. The mixture was compressed at a pressure of  $20 \text{ kg cm}^{-2}$  into a pellet-shaped SRF with a diameter of approximately 5 cm.

Table 3 shows the formulas for the various SRFs. The mass fraction of the treated waste lubricant, which ranged from 33% to 70%, was the main operational factor. The wood dust served as an additive, and the treated waste lubricant and wood dust accounted for approximately 90% of the mass of the SRF. The percentage of the added coal ash ranged from 5 to 10%, which improved the physical strength of the mixture, and 0.5% bentonite was consistently added to bind the mixture. The theoretical low heating value was calculated from adding the products of the mass fractions and the low heating value of each material. The relative errors between the theoretical



**Table 1.** Properties of the raw and treated waste lubricants (n = 3).

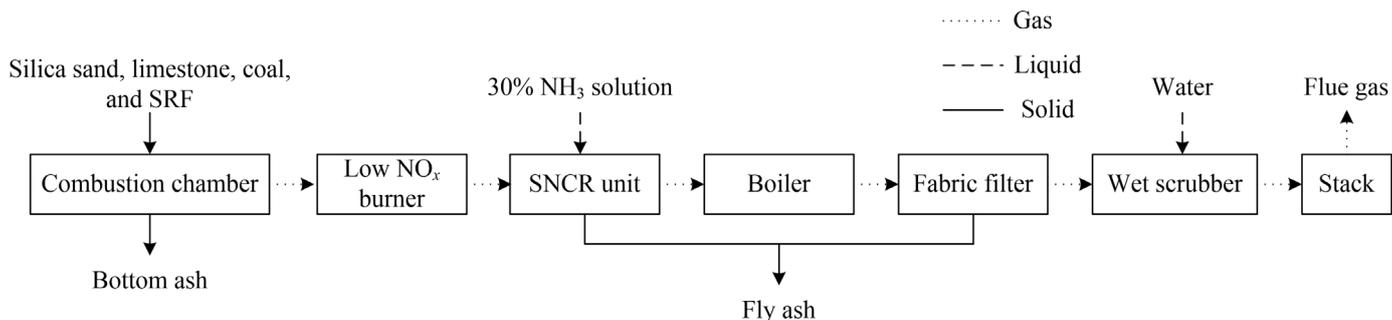
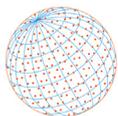
Item	Raw waste lubricants		Treated waste lubricants		
	Average	RSD (%)	Average	RSD (%)	
Proximate analysis	Water (%)	24.6	13.7	8.6	11.5
	Ash content (%)	2.9	12.8	3.22	13.7
	Combustible content (%)	72.4	3.05	88.2	16.8
Combustible content	C (%)	56.7	15.4	77.1	16.6
	H (%)	7.74	17.8	4.69	18.7
	O (%)	7.27	11.5	6.22	12.3
	N (%)	0.05	22.3	0.03	28.6
	S (%)	0.04	27.7	0.05	15.2
	Cl (%)	0.01	14.1	0.01	17.3
	Metals	Al (mg kg <sup>-1</sup> )	9,700	13.8	1,210
Ca (mg kg <sup>-1</sup> )		3,140	8.0	2,850	20.1
Cd (mg kg <sup>-1</sup> )		6.8	12.4	3.47	15.7
Cr (mg kg <sup>-1</sup> )		75.4	17.7	31.6	18.9
Cu (mg kg <sup>-1</sup> )		804	15.5	357	15.6
Fe (mg kg <sup>-1</sup> )		18,500	8.7	3,670	21.3
Mn (mg kg <sup>-1</sup> )		44.5	4.5	12.3	15.8
Ni (mg kg <sup>-1</sup> )		283	37.6	72.8	16.4
Pb (mg kg <sup>-1</sup> )		35	86.1	12.0	8.9
Zn (mg kg <sup>-1</sup> )		850	25.4	105	12.3
Low heating value (kcal kg <sup>-1</sup> )	6,940	11.5	8,690	18.4	

**Table 2.** Properties of the additives for SRF (n = 3).

Item	Wood dust		Bentonite		Coal ash		
	Average	RSD (%)	Average	RSD (%)	Average	RSD (%)	
Proximate analysis	Water content (%)	11.7	10.8	9.5	1.90	0.3	17.6
	Ash content (%)	0.43	13.4	10.1	26.8	90.2	11.3
	Combustible content (%)	88.4	15.3	80.4	0.198	9.57	8.98
Elements	Al (mg kg <sup>-1</sup> )	1,060	73.7	13,900	21.4	1,220	2.0
	Ca (mg kg <sup>-1</sup> )	10.0	0.6	23,300	12.5	256	9.2
	Cd (mg kg <sup>-1</sup> )	0.9	90.6	2.61	14.7	N.D.	N.A.
	Cr (mg kg <sup>-1</sup> )	N.D.	N.A.	58	8.5	N.D.	N.A.
	Cu (mg kg <sup>-1</sup> )	6.3	25.2	10.5	55.5	6.27	21.4
	Fe (mg kg <sup>-1</sup> )	131.9	9.1	26,500	7.3	331	9.5
	Mn (mg kg <sup>-1</sup> )	58.2	10.1	251	5.1	N.D.	N.A.
	Ni (mg kg <sup>-1</sup> )	2.66	12.4	98.7	5.7	11.8	17.0
	Pb (mg kg <sup>-1</sup> )	9.05	24.5	23.9	45.5	8.33	7.2
	Zn (mg kg <sup>-1</sup> )	27.6	25.3	267	16.5	18.9	39.8
	Cl (mg kg <sup>-1</sup> )	2,650	15.4	1.2	18.8	807	32.1
S (mg kg <sup>-1</sup> )	2,810	18.7	504	12.1	529	18.9	
Low heating value (kcal kg <sup>-1</sup> )	3,300	15.2	3,650	8.6	63.7	10.6	

**Table 3.** Formulas for the SRFs in different runs.

Item	Run-1	Run-2	Run-3	Run-4	Run-5	Run-6	Run-7	Run-8
Treated waste lubricant (%)	33	40	45	50	55	60	64	70
Wood dust (%)	60	50	42	40	35	35	30	19.5
Bentonite (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Coal ash (%)	6.5	9.5	12.5	9.5	9.5	4.5	5.5	10.0
Measured low heating value (kcal kg <sup>-1</sup> )	4,450	4,610	5,030	5,620	5,610	5,840	6,210	6,040
Theoretical low heating value (kcal kg <sup>-1</sup> )	4,870	5,151	5,324	5,690	5,960	6,359	6,575	6,754
Relative error (%)	-8.62	-10.7	-6.08	-1.59	-6.04	-8.80	-5.71	-11.2



**Fig. 3.** Process flow at the cogeneration plant for the reclamation of SRF.

and measured low heating values were mostly less than 10%. To meet the fuel specification requirements for the cogeneration plant, the ingredients in the SRF and their proportions in the experiments were as follows: treated waste lubricant (60 wt%), wood dust (35 wt%), coal ash (4.5%), and bentonite (0.5 wt%).

## 2.2 Reclamation of SRF in a Steam Generation Plant

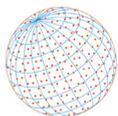
The remolded SRF was transported to a cogeneration plant located in Taichung City. The process flow diagram is shown in Fig. 3. The input materials were fed via a conveyor belt into a fluidized-bed combustion chamber with a capacity of 2 ton hr<sup>-1</sup>. Silica sand and limestone were added to distribute the heat uniformly over the combustion chamber. The worn supplemental materials, silica sand and limestone, were discharged from the furnace with the bottom ash or fly ash. The original input material used for feed at this cogeneration plant was coal, with a low heating value of approximately 5,500 kcal kg<sup>-1</sup>. Therefore, the formulas for the SRFs chosen for use in the tests were those made in run-3. The combustion tests were divided into control and experimental groups, and each group underwent three tests. The input material for the control group was 100% coal. For the experimental group, SRF and coal accounted for 40% and 60% of the input material mass, respectively. The combustion temperature was maintained at 750 to 800°C, and [O<sub>2</sub>] was controlled at under 10% to reduce the formation of NO<sub>x</sub>. The combustion residue was discharged into the bottom ash pit and cooled using water. The flue gas was emitted from the furnace into a low-NO<sub>x</sub> burner to inhibit NO<sub>x</sub> formation at 800 to 850°C. The flue gas passed through an SNCR (selective non-catalytic reduction) unit with an injection of 30% NH<sub>3</sub> solution, which is a common process used to reduce NO<sub>x</sub> (Yue *et al.*, 2020). The reduction reaction is shown as Eq. (1).



The flue gas then passed into a boiler. The generated amount, the rated working pressure, and the rated temperature of the steam were 10 to 12 ton hr<sup>-1</sup>, 20 kg cm<sup>-2</sup>, and 180 to 200°C, respectively. The flue gas was cooled to approximately 180°C and passed through into a fabric filter with a filtering velocity of 0.5 m min<sup>-1</sup>. Next, a wet scrubber was set up to remove acid gas (HCl and SO<sub>2</sub>) via an injection of a 40% NaOH solution with liquid to gas ratio of 2 L m<sup>-3</sup>, and the treated flue gas was then emitted to the ambient air. The fly ashes emitted from the boiler, the fabric filter, and the wet scrubber were all collected together as the total fly ash.

## 2.3 Sampling of Flue Gas and Solid Specimens

The flue gas was sampled at the stack. Before sampling the PCDD/Fs, the collection efficiency of the sampling train was measured with the addition of specific amounts of surrogate standards pre-labeled with isotopes, including <sup>37</sup>C<sub>14</sub>-2,3,7,8-TeCDD, <sup>13</sup>C<sub>12</sub>-1,2,3,4,7,8-HxCDD, <sup>13</sup>C<sub>12</sub>-2,3,4,7,8-PeCDF, <sup>13</sup>C<sub>12</sub>-1,2,3,4,7,8-HxCDF, and <sup>13</sup>C<sub>12</sub>-1,2,3,4,7,8,9-HpCDF. A standard sampling procedure was used in the experiments to measure the PCDD/Fs in the flue gas, following the instructions issued by the TEPA, for which the detailed procedures were reported in a previous study (TEPA, 2010; Kuo *et al.*, 2019).



The sampling and analysis of the metals in the flue gas followed the standard method established by the NIEA A302.72C (TEPA, 2006). A sampling train with a cooling device, a holder with a fiberglass filter, a series of impingers, a pump, and a flow meter was used for sampling the flue gas isokinetically. The average flow rate was set at  $5 \text{ L min}^{-1}$ , and the sampling time was more than 3 hrs. The sampling and analytical procedure used to measure the metals in the flue gas were reported in previous studies in detail (Tsai *et al.*, 2018; Chen *et al.*, 2018).

A flue gas analyzer (Horiba, PG-350) was used to continuously measure the concentrations of  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$ , and  $\text{SO}_x$  in the flue gas. In addition, bottom ash and mixed fly ash were collected from the ash pits for further analysis.

## 2.4 Analyses of PCDD/Fs, Metal Content, and Metal Leaching Behavior

The pretreatment of the solid specimens used in the PCDD/F analysis was conducted using the following steps: 1) Extraction with a mixed solvent of half-and-half *n*-hexane and dichloromethane, 2) determining the nitrogen-blowing concentration, 3) cleanup via silica gel, and 4) determining the nitrogen-blowing re-concentration. The solutions were then analyzed using a high-resolution gas chromatograph (Hewlett-Packard 6970 Series gas, CA) and a high-resolution mass spectrometer (Micromass Autospec Ultima, Manchester, UK) to identify 17 PCDD/F species. The detailed procedures for the PCDD/F analysis were reported in previous studies (Tsai *et al.*, 2018; Kuo *et al.*, 2019).

The procedure used to determine the metal content in the solid specimens was modified from the standard method given in NIEA R317.11C (TEPA, 2014). The solid specimens were all pulverized to particle sizes smaller than  $150 \mu\text{m}$  (mesh 100) to ensure consistent digestion efficiency. The pulverized solid specimens ( $\sim 0.1 \text{ g}$ ) were held in Teflon vessels to which a mixed acid composed of 3 mL HCl (32 wt%) and 3 mL  $\text{HNO}_3$  (67 wt%) was added. The vessels were sealed and heated using a microwave digester (MARS Xpress, CEM). The heating program was as follows: heating to  $210^\circ\text{C}$  at a rate of  $6^\circ\text{C min}^{-1}$ , holding isothermally for 20 min, and cooling down to room temperature with ventilation. The digests were diluted with deionized water to 25 mL and then filtrated using mixed cellulose ester filters.

A toxicity characteristic leaching procedure (TCLP) was used to evaluate the hazardous metal mobility of the bottom ash and mixed fly ash. An extraction solution ( $\text{pH} = 4.93 \pm 0.05$ ) was prepared using 5.7 mL of glacial acetic acid and 64.3 mL of NaOH solution (1 N), which were mixed and diluted to 1000 mL using deionized water. The pulverized specimen and the prepared extraction solution were mixed at a mass ratio of solid:liquid = 1:20. The mixture was rotated overhead at a rate of  $30 \text{ turn min}^{-1}$  for 24 hrs. The leachate was separated from the solid specimens, acidified by adding 0.5 mL of concentrated  $\text{HNO}_3$ , and filtered for the metal analysis. The detailed steps, including preparation of the extraction solution, the leaching conditions, dilution, digestion, and filtration, all followed the standard procedure regulated by the TEPA (2016). The metal concentrations, including Al, As, Ba, Ca, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, and Zn in the solution and the digests were measured using atomic absorption spectroscopy (AAS, Agilent technologies 55AA).

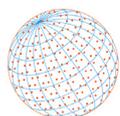
## 3 RESULTS AND DISCUSSION

### 3.1 Property of Input Materials

The properties of the SRF and coal are shown in Table 4. The SRF had 77.8% combustible content, 9.6% water content, and 12.6% water content. The coal had approximately an equal fraction of combustible content but a higher fraction of ash content than the SRF. The low heating value of the SRF ( $5,690 \text{ kcal kg}^{-1}$ ) was slightly higher than that of coal ( $5,340 \text{ kcal kg}^{-1}$ ). In terms of the content of metal species, the SRF had Fe ( $3,950 \text{ mg kg}^{-1}$ ), Ca ( $3,220 \text{ mg kg}^{-1}$ ), and Al ( $2,220 \text{ mg kg}^{-1}$ ), and the coal had Mn ( $33,100 \text{ mg kg}^{-1}$ ), Fe ( $24,700 \text{ mg kg}^{-1}$ ), and Ca ( $3,650 \text{ mg kg}^{-1}$ ).

### 3.2 Pollutant Concentrations in the Flue Gas

The concentrations of the air pollutants in the flue gas are shown in Table 5. For Group I, the average concentrations of  $[\text{O}_2]$ ,  $[\text{CO}_2]$ , and  $[\text{CO}]$  in the flue gas were 8.3%, 11.5%, and 45 ppm, respectively. The flue gas in Group II had  $[\text{O}_2]$ ,  $[\text{CO}_2]$ , and  $[\text{CO}]$  at concentrations of 6.5%, 12.4%, and 35 ppm, respectively. The averaged combustion efficiencies ( $= ([\text{CO}_2]/[\text{CO}_2] + [\text{CO}]) \times 100\%$ )



**Table 4.** Properties of the input materials.

Item	Coal		SRF		
	Average	RSD(%)	Average	RSD(%)	
Proximate analysis	Water content (%)	5.2	17.2	12.6	7.8
	Ash content (%)	16.3	28.5	9.6	25.7
	Combustible content (%)	78.5	24.4	77.8	3.7
Metals	Al (mg kg <sup>-1</sup> )	548	16.3	2,220	8.23
	Ca (mg kg <sup>-1</sup> )	3,650	18.3	3,220	27.7
	Cd (mg kg <sup>-1</sup> )	3.82	15.7	1.77	36.3
	Cr (mg kg <sup>-1</sup> )	7.32	16.1	17.4	21.0
	Cu (mg kg <sup>-1</sup> )	25.0	22.9	155	27.4
	Fe (mg kg <sup>-1</sup> )	24,700	28.1	3,950	8.83
	Mn (mg kg <sup>-1</sup> )	33,100	12.8	1.0	2.1
	Ni (mg kg <sup>-1</sup> )	0.75	8.9	41.5	17.9
	Pb (mg kg <sup>-1</sup> )	3.38	15.4	9.99	15.8
	Zn (mg kg <sup>-1</sup> )	1.1	18.1	59.0	22.9
	Cl (mg kg <sup>-1</sup> )	184	15.6	751	18.4
S (mg kg <sup>-1</sup> )	846	16.7	900	15.6	
Low heating value (kcal kg <sup>-1</sup> )	5,340	22.1	5690	13.2	

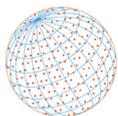
**Table 5.** Concentrations of the pollutants in the flue gas.

Item	Group I (Coal)		Group II (60% Coal + 40% SRF)		Regulated standard
	Average	RSD(%)	Average	RSD(%)	
O <sub>2</sub> (%)	8.3	6.3	6.5	8.5	–
CO <sub>2</sub> (%)	11.5	4.5	12.4	5.4	–
CO (ppm)	45	10.1	35	17.4	350
NO <sub>x</sub> (ppm)	160	18.5	120	12.3	220
SO <sub>x</sub> (ppm)	14	15.7	19	11.4	220
Particulate (mg Nm <sup>-3</sup> )	5.0	16.7	2.0	20.4	80
PCDD/Fs (ng I-TEQ Nm <sup>-3</sup> )	0.0102	25.8	0.003	33.3	0.5
Cd (mg Nm <sup>-3</sup> )	0.00134	18.4	0.00128	17.7	0.04
Cr (mg Nm <sup>-3</sup> )	0.0147	12.6	0.0128	13.6	–
Cu (mg Nm <sup>-3</sup> )	0.00271	11.5	0.00133	22.4	–
Hg (mg Nm <sup>-3</sup> )	0.00021	10.8	0.00015	18.5	0.05
Ni (mg Nm <sup>-3</sup> )	0.00317	13.4	0.00656	21.1	–
Pb (mg Nm <sup>-3</sup> )	0.035	17.4	0.0122	15.6	0.5

for Groups I and II remained excellent (99.96% and 99.97%) and were roughly equal. The average concentration of [SO<sub>2</sub>] in the flue gas in Group II (19 ppm) was slightly higher than that in Group I (14 ppm). However, the concentrations were only about one order lower than the regulated standard (TEPA, 2020a). The [NO<sub>x</sub>] in the flue gas in Group I was 160 ppm, which was fairly close to the regulated standard (220 ppm), and it was slightly reduced to 120 ppm in Group II (TEPA, 2020a). This can be explained by the fact that the [O<sub>2</sub>] in Group II was further reduced to 6.5%, and thus, the formation of thermal NO<sub>x</sub> was partly reduced (see Eq. (2)).



When the coal was replaced with SRF, the PCDD/F concentrations in the flue gas were reduced from 0.01 ng I-TEQ Nm<sup>-3</sup> (Group II) to 0.003 ng I-TEQ Nm<sup>-3</sup> (Group I), which were both much lower than the regulated standard (0.5 ng I-TEQ Nm<sup>-3</sup>). The low PCDD/F level was attributed to excellent combustion efficiency and the injection of activated carbon, which was also reported in a previous study (Chen *et al.*, 2020). Regarding the metal species, the concentrations in the flue gas in both groups were 1 to 2 orders lower than those specified in the regulated standard (TEPA, 2020a).



The substitution of SRF for coal appeared to further reduce the concentrations of most of the metal species in the flue gas.

### 3.3 Pollutant Composition in Mixed Fly Ashes

Table 6 shows the PCDD/F content and metal composition of ashes in the two groups. Similar to the results of the flue gas analysis, the PCDD/F levels in the bottom ash (0.0045 ng I-TEQ g<sup>-1</sup>) and fly ashes (0.0003 ng I-TEQ g<sup>-1</sup>) in Group II were slightly lower than those (0.0049 ng I-TEQ g<sup>-1</sup> and 0.0005 ng I-TEQ g<sup>-1</sup>) in Group I. However, the PCDD/F levels of these ashes were all much lower than the regulated standard for hazardous materials (1 ng I-TEQ g<sup>-1</sup>) (TEPA, 2020b).

Fig. 4 shows the PCDD/F patterns of the flue gas, fly ashes, and bottom ash. For Group I, the PCDD/F profiles for the flue gas and fly ashes were very similar, and the PCDD/F mass was mainly distributed in the form of OCDD, 1,2,3,4,6,7,8-HpCDF, 1,2,3,4,6,7,8-HpCDD, and OCDF. On the other hand, the PCDD/F mass of the bottom ash was mainly distributed in the form of OCDD (54.9%), 1,2,3,4,6,7,8-HpCDD (14.8%), and OCDF (13.0%). For Group II, the PCDD/F mass concentrations in the flue gas were mainly distributed in the form of 1,2,3,4,6,7,8-HpCDF (22.4%), OCDF (20.8%), and OCDD (18.1%). The fly ashes mainly had PCDD/F mass concentrations in the form of OCDD (27.8%) and 1,2,3,4,6,7,8-HpCDD (38.2%). Similar to the bottom ash in Group I, the PCDD/F mass concentrations of the bottom ash in Group II were mainly in the form of OCDF (34.6%), OCDD (17.0%), 1,2,3,4,6,7,8-HpCDF (13.2%), and 1,2,3,4,6,7,8-HpCDD (9.32%). Overall, the PCDD/F mass concentrations in the two groups mainly existed as 7-Cl and 8-Cl PCDD/Fs, and the addition of SRF did not make any significant difference.

### 3.4 Mass Distribution and Emission Behavior of Pollutants among Output Materials

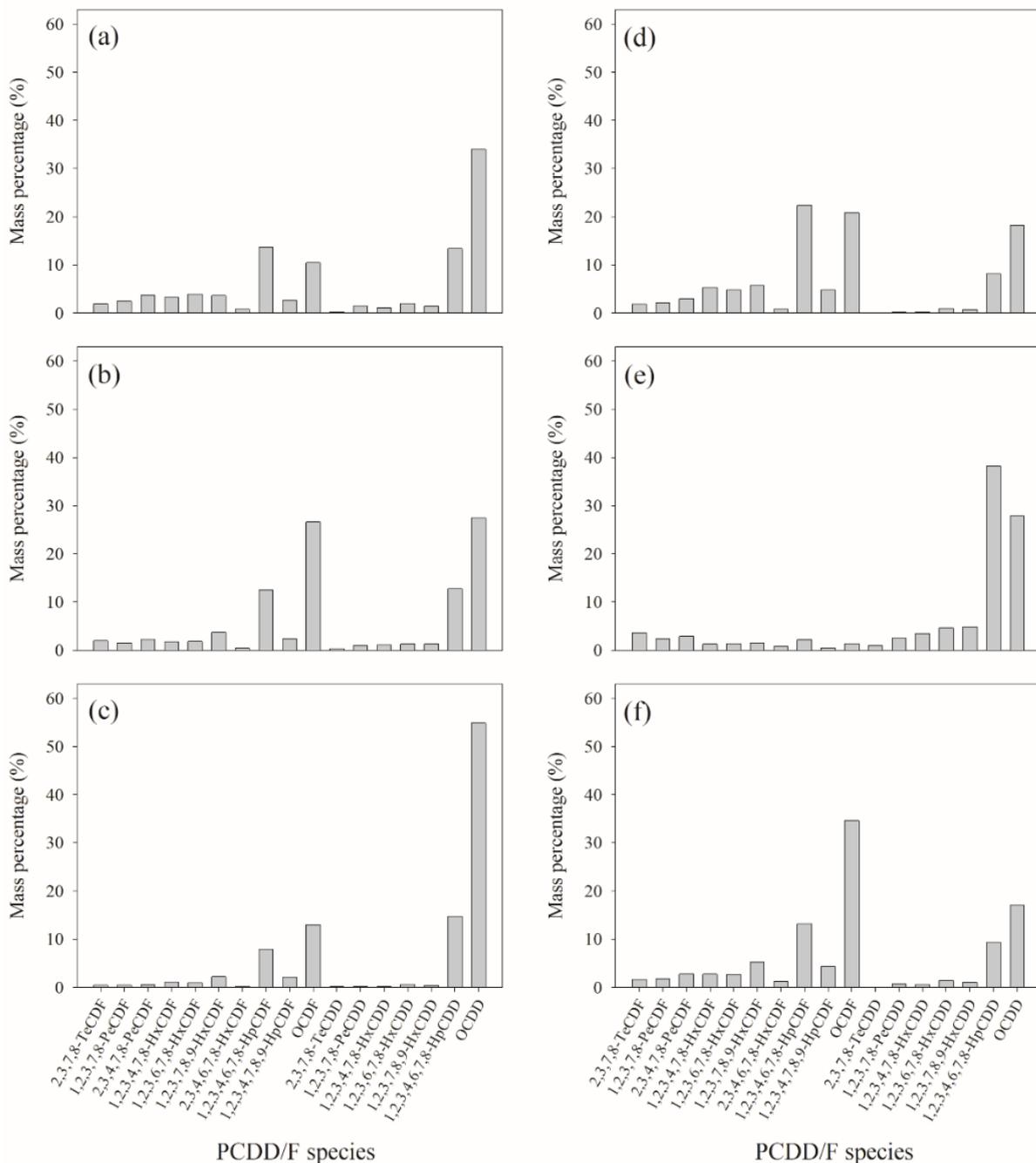
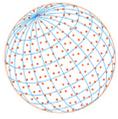
Table 7 shows the mass distributions and emission factors of PCDD/Fs and heavy metals among the output materials. For Group I, the PCDD/Fs were mainly discharged from the fly ashes (61.8%), for which the emission factor was 388 ng I-TEQ ton<sup>-1</sup>. Similarly, the fly ashes also served as the main discharge route (75.4%) in Group II, and the emission factor was further reduced to 232 ng I-TEQ ton<sup>-1</sup>. The substitution of SRF for coal reduced the PCDD/F emissions by 40% but did not change the discharge route. This was probably due to the fact that SRF contains approximately 10% intra oxygen, which improves combustion and maintains the O<sub>2</sub> in the flue gas at a relatively low concentration, thus retarding the formation of PCDD/Fs. In comparison to the results found in a previous study, the cogeneration plant emission factor was approximately 3 orders lower than that of the municipal solid waste incinerator, and the main discharge route was also from the fly ashes (Wang *et al.*, 2010).

### 3.5 Recycling Characteristics of the Ashes

Table 8 shows the TCLP results for the ashes. In the case of both the bottom ash and fly ashes,

**Table 6.** PCDD/F content and metal composition of the ashes in both groups.

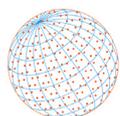
Item	Group I (Coal)		Group II (Coal + SRF)	
	Bottom ash	Fly ash	Bottom ash	Fly ash
PCDD/Fs (ng I-TEQ g <sup>-1</sup> )	0.0005	0.0049	0.0003	0.0045
Al (mg kg <sup>-1</sup> )	12,400	3,850	18,800	3,650
Ca (mg kg <sup>-1</sup> )	85,700	12,500	98,400	11,500
Cd (mg kg <sup>-1</sup> )	2.28	20.1	1.05	12.1
Cr (mg kg <sup>-1</sup> )	6.79	104	23.8	329
Cu (mg kg <sup>-1</sup> )	23.7	205	119	922
Fe (mg kg <sup>-1</sup> )	3,840	2,580	5,710	3,240
Hg (mg kg <sup>-1</sup> )	0.005	0.18	0.004	0.11
Mn (mg kg <sup>-1</sup> )	556	338	453	185
Ni (mg kg <sup>-1</sup> )	250	2.5	417	15.7
Pb (mg kg <sup>-1</sup> )	2.1	25.8	4.32	61.0
Zn (mg kg <sup>-1</sup> )	115	655	161	983



**Fig. 4.** PCDD/F patterns for the output materials: (a) flue gas (Group I); (b) fly ash (Group I); (c) bottom ash (Group I); (d) flue gas (Group II); (e) fly ash (Group II); (f) bottom ash (Group II).

**Table 7.** PCDD/Fs mass distribution, emission factors, and metals among the output materials for the two groups.

Item	Group I (Coal)				Group II (Coal + SRF)			
	Bottom ash (%)	Fly ashes (%)	Flue gas (%)	Emission factor (mg ton <sup>-1</sup> )	Bottom ash (%)	Fly ashes (%)	Flue gas (%)	Emission factor (mg ton <sup>-1</sup> )
PCDD/Fs	21.02	61.8	17.2	388 ng I-TEQ ton <sup>-1</sup>	16.8	75.4	7.8	232 ng I-TEQ ton <sup>-1</sup>
Cd	27.3	72.1	0.64	1,360	22.2	76.6	1.3	614
Cr	17.6	80.9	1.53	6,290	19.3	80.2	0.5	15,900
Hg	7.42	80.1	12.48	11.0	9.1	75.0	15.9	5.7
Ni	99.7	0.30	0.05	40,900	98.8	1.1	0.1	54,600
Pb	18.7	68.9	12.47	1,830	18.6	78.9	2.5	3,010



**Table 8.** TCLP results for the ashes in both groups (units: in mg L<sup>-1</sup>).

Item	Group I (Coal)		Group II (Coal + SRF)		Regulated standard
	Bottom ash	Fly ashes	Bottom ash	Fly ashes	
As	0.17	0.034	0.12	0.025	5.0
Ba	0.31	0.15	0.23	0.11	100
Cd	N.D.	N.D.	N.D.	N.D.	1.0
Cr	0.45	0.115	0.11	0.02	5.0
Cu	0.55	0.1	0.38	N.D.	15.0
Hg	N.D.	N.D.	N.D.	N.D.	0.2
Pb	N.D.	N.D.	N.D.	N.D.	5.0
Se	N.D.	N.D.	N.D.	N.D.	1.0

**Table 9.** Metal oxide content in the ashes for Group I and Group II (units: in %).

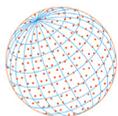
Item	Group I		Group II	
	Bottom ash	Fly ash	Bottom ash	Fly ash
Al <sub>2</sub> O <sub>3</sub>	28.7	21.4	26.6	20.88
CaO	0.572	4.17	0.997	5.88
Fe <sub>2</sub> O <sub>3</sub>	2.17	4.87	3.23	5.45
SiO <sub>2</sub>	64.1	50.84	65.8	43.45
Cl	0.0015	0.018	0.0036	0.0125

the leaching concentrations of the metals in both groups were all N.D. or much lower than the regulated standard for hazardous materials (TEPA, 2020b). The leaching concentrations of the ashes in Group II were slightly lower than those in Group I. In addition, the PCDD/F content in the ashes was lower than the regulated standard of hazardous materials, as previously mentioned. Therefore, the bottom ash and fly ashes were classified as non-hazardous materials and could be directly recycled as building materials. Table 9 shows the Al, Ca, Fe, and Si oxides in the bottom ash and fly ashes. For the bottom ash, SiO<sub>2</sub> accounted for 64.1% and 65.8% in groups I and II, respectively. Next to SiO<sub>2</sub>, the fractions of Al<sub>2</sub>O<sub>3</sub> were 28.7% and 26.6% in Groups I and II, respectively. The percentages of Fe<sub>2</sub>O<sub>3</sub> and CaO were both less than 5%. For the fly ashes, SiO<sub>2</sub> was still the main oxide in both Groups I (50.84%) and II (43.45%), and Al<sub>2</sub>O<sub>3</sub> was also the secondary oxide in Groups I (21.4%) and II (20.88%). The percentages of CaO and Fe<sub>2</sub>O<sub>3</sub> were all approximately 5%. For recycling as the raw materials in cement, the total Al<sub>2</sub>O<sub>3</sub>, CaO, Fe<sub>2</sub>O<sub>3</sub>, and SiO<sub>2</sub> is required to be higher than 85%. The bottom ashes met this requirement, but the fly ashes did not. Therefore, the bottom ashes could be directly recycled as an additive of cement. On the other hand, the cementation of fly ashes to form other building materials, such as road pavement, could be taken into consideration.

### 3.6 Economic Analysis for Recovering Waste Lubricant and Reclamation of SRF

Table 10 shows the results for the economic analysis of the recovery of waste lubricant. The treatment plant can obtain a treatment income of 260 USD ton<sup>-1</sup> from the food-can factory. 0.17 of a ton of wastewater was discharged during the treatment of 1 ton of waste lubricant, and the treatment cost for the wastewater was 30 USD ton<sup>-1</sup>. The cost of the additives for SRF, including wood dust, bentonite, and coal ash was 50, 100, and -20 USD ton<sup>-1</sup>, respectively. The price at which it was sold to the cogeneration plant was 30 USD ton<sup>-1</sup>, which was the income for the treatment plant. Recovery of 1 ton of waste lubricant produced 1.381 tons of SRF, and the operating cost for the SRF was about 80 USD ton<sup>-1</sup>. The net revenue for recovering 1 ton of waste lubricant was 119 USD ton<sup>-1</sup>. The capacity of this treatment plant was 30 tons day<sup>-1</sup>, and the operating days were 300 days per year. Therefore, the annual gross revenue for this treatment plant was 1,071,000 USD.

The heating value of the SRF (5,690 kcal kg<sup>-1</sup>) was approximately equal to that of coal (5,340 kcal kg<sup>-1</sup>), but the price was about half (32 USD ton<sup>-1</sup>) that of coal (60 USD ton<sup>-1</sup>). The capacity of the cogeneration plant was 2 tons coal feeding per hour, where with a 50% replacement of coal

**Table 10.** Economic analysis of recovery of waste lubricant.

Item	Mass (ton)	Price (USD ton <sup>-1</sup> )	Income/Outcome (USD)	Annotation
Waste lubricant	1	260	+260	Treatment fee from food-can factory
Treated lubricant	0.83	–	–	
Wastewater	0.17	30	–51	Wastewater treatment cost
Wood dust	0.484	50	–24.2	
Bentonite	0.007	100	–0.7	
Coal ash	0.06	20	1.2	
Operating cost	1.381	80	–110.5	Operating costs for 1 ton of SRF (including electricity, water, manpower, and maintenance of facility)
SRF	1.381	32	44.2	Income of selling SRF to cogeneration plant
Net revenue	–	–	119	

with SRF, it was 1 ton hr<sup>-1</sup>. The cogeneration plant was operated 24 hrs a day, 330 days per year. The savings for fuel was as high as 221,760 USD per year. Therefore, the substitution of SRF for coal was feasible from an economic point of view.

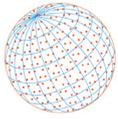
## 4 CONCLUSIONS

In this study, the combustion performance of coal and was compared with a mixture of coal and SRF in a cogeneration plant. There were several conclusions drawn suggesting that it is feasible to replace coal with this SRF transformed from recovered waste lubricant as follows:

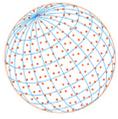
1. For Group I (100% coal), the concentration of the pollutants in the flue gas was much lower than the regulated standard, with the exception of [NO<sub>x</sub>].
2. In the scenario where 40% of the coal was replaced with SRF, the concentrations of NO<sub>x</sub> and PCDD/Fs in the flue gas were 25% and 70%, respectively.
3. The PCDD/F emission factor in the cogeneration plant was 3 orders lower than that in the municipal solid waste incinerator. The substitution of SRF for coal further reduced the PCDD/F emissions by 40%.
4. The bottom ash and fly ashes from this cogeneration plant were considered general industrial waste and could be directly recycled as a cement additive.
5. The treatment plant could obtain a net revenue of 119 USD ton<sup>-1</sup> from recovering waste lubricant. The replacement of coal with SRF could decrease the consumption of coal and increase the profits for the plant.
6. The pollution characteristics of this plant were slightly improved by substitution of SRF, and the ashes still could be directly recycled as cement additives.

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