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

Yi-Ming Kuo1*, Shih-Wei Huang2,3, Wang Yu Kuan4

1 Department of Safety Health and Environmental Engineering, Chung Hwa University of Medical Technology, Tainan 71703, Taiwan
2 Institute of Environmental Toxin and Emerging Contaminant, Cheng Shiu University, Kaohsiung 83347, Taiwan
3 Center for Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, Kaohsiung 83347, Taiwan
4 She Ching Enterprise Co., Ltd., Tainan 74443, Taiwan

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⁻³) were slightly lower than those in the runs with coal (0.102 ng I-TEQ Nm⁻³). According to the monitoring data for CO, O₂, NOₓ 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

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 waste into energy and 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⁻¹. 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⁻¹. 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⁻¹.
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 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 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 (123,900 mg kg$^{-1}$), Ca (23,300 mg kg$^{-1}$), and Fe (26,500 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 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 (%)     | 56.7    | 15.4    | 77.1    | 16.6    |
| C (%)                       | 7.74    | 17.8    | 4.69    | 18.7    |
| H (%)                       | 7.27    | 11.5    | 6.22    | 12.3    |
| O (%)                       | 0.05    | 22.3    | 0.03    | 28.6    |
| N (%)                       | 0.04    | 27.7    | 0.05    | 15.2    |
| S (%)                       | 0.01    | 14.1    | 0.01    | 17.3    |
| Cl (%)                      |         |         |         |         |
| Metals                      |         |         |         |         |
| Al (mg kg⁻¹)                | 9,700   | 13.8    | 1,210   | 18.6    |
| Ca (mg kg⁻¹)                | 3,140   | 8.0     | 2,850   | 20.1    |
| Cd (mg kg⁻¹)                | 6.8     | 12.4    | 3.47    | 15.7    |
| Cr (mg kg⁻¹)                | 75.4    | 17.7    | 31.6    | 18.9    |
| Cu (mg kg⁻¹)                | 804     | 15.5    | 357     | 15.6    |
| Fe (mg kg⁻¹)                | 18,500  | 8.7     | 3,670   | 21.3    |
| Mn (mg kg⁻¹)                | 44.5    | 4.5     | 12.3    | 15.8    |
| Ni (mg kg⁻¹)                | 283     | 37.6    | 72.8    | 16.4    |
| Pb (mg kg⁻¹)                | 35      | 86.1    | 12.0    | 8.9     |
| Zn (mg kg⁻¹)                | 850     | 25.4    | 105     | 12.3    |
| Low heating value (kcal kg⁻¹) | 6,940   | 11.5    | 8,690   | 18.4    |

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

| Item                        | Wood dust | Average | RSD (%) | Bentonite | Average | RSD (%) | Coal ash | 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⁻¹)                | 1,060     | 73.7    | 13,900  | 21.4      | 1,220   | 2.0     |
| Ca (mg kg⁻¹)                | 10.0      | 0.6     | 23,300  | 12.5      | 256     | 9.2     |
| Cd (mg kg⁻¹)                | 0.9       | 90.6    | 2.61    | 14.7      | N.D.    | N.A.    |
| Cr (mg kg⁻¹)                | N.D.      | N.A.    | 58      | 8.5       | N.D.    | N.A.    |
| Cu (mg kg⁻¹)                | 6.3       | 25.2    | 10.5    | 55.5      | 5.5     | 21.4    |
| Fe (mg kg⁻¹)                | 131.9     | 9.1     | 26,500  | 7.3       | 331     | 9.5     |
| Mn (mg kg⁻¹)                | 58.2      | 10.1    | 251     | 5.1       | N.D.    | N.A.    |
| Ni (mg kg⁻¹)                | 2.66      | 12.4    | 98.7    | 5.7       | 11.8    | 17.0    |
| Pb (mg kg⁻¹)                | 9.05      | 24.5    | 23.9    | 45.5      | 8.33    | 7.2     |
| Zn (mg kg⁻¹)                | 27.6      | 25.3    | 267     | 16.5      | 18.9    | 39.8    |
| Cl (mg kg⁻¹)                | 2,650     | 15.4    | 1.2     | 18.8      | 807     | 32.1    |
| S (mg kg⁻¹)                 | 2,810     | 18.7    | 504     | 12.1      | 529     | 18.9    |
| Low heating value (kcal kg⁻¹) | 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⁻¹) | 4,450 | 4,610 | 5,030 | 5,620 | 5,610 | 5,840 | 6,210 | 6,040 |
| Theoretical low heating value (kcal kg⁻¹) | 4,870 | 5,151 | 5,324 | 5,690 | 5,960 | 6,359 | 6,575 | 6,754 |
| Relative error (%)          | -8.6  | -10.7 | -6.08 | -1.59 | -6.04 | -8.8  | -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⁻¹. 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⁻¹. 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 [O₂] was controlled at under 10% to reduce the formation of NOₓ. 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-NOₓ burner to inhibit NOₓ formation at 800 to 850°C. The flue gas passed through an SNCR (selective non-catalytic reduction) unit with an injection of 30% NH₃ solution, which is a common process used to reduce NOₓ (Yue et al., 2020). The reduction reaction is shown as Eq. (1).

\[
4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
\]  

(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⁻¹, 20 kg cm⁻², 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⁻¹. Next, a wet scrubber was set up to remove acid gas (HCl and SO₂) via an injection of a 40% NaOH solution with liquid to gas ratio of 2 L m⁻³, 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 \[^{37}\text{C}_{14-2},3,7,8-\text{TeCDD}, \^{13}\text{C}_{12-1,2,3,4,7,8-\text{HxCDD}}, \^{13}\text{C}_{12-2,3,4,7,8-\text{PeCDF}}, \^{13}\text{C}_{12-1,2,3,4,7,8-\text{HxCDF}}, \text{and} \^{13}\text{C}_{12-1,2,3,4,7,8,9-\text{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 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 O₂, CO₂, CO, NOₓ, and SOₓ 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 µm (mesh 100) to ensure consistent digestion efficiency. The pulverized solid specimens (~0.1 g) were held in Teflon vessels to which a mixed acid composed of 3 mL HCl (32 wt%) and 3 mL HNO₃ (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°C at a rate of 6 °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 (pH = 4.93 ± 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 turn min⁻¹ for 24 hrs. The leachate was separated from the solid specimens, acidified by adding 0.5 mL of concentrated HNO₃, 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% ash 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 kcal kg⁻¹) was slightly higher than that of coal (5,340 kcal kg⁻¹). In terms of the content of metal species, the SRF had Fe (3,950 mg kg⁻¹), Ca (3,220 mg kg⁻¹), and Al (2,220 mg kg⁻¹), and the coal had Mn (33,100 mg kg⁻¹), Fe (24,700 mg kg⁻¹), and Ca (3,650 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 [O₂], [CO₂], and [CO] in the flue gas were 8.3%, 11.5%, and 45 ppm, respectively. The flue gas in Group II had [O₂], [CO₂], and [CO] at concentrations of 6.5%, 12.4%, and 35 ppm, respectively. The averaged combustion efficiencies (= ([CO₂]/[CO₂] + [CO]) × 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⁻¹)                | 548     | 16.3   | 2,220   | 8.23   |
| Ca (mg kg⁻¹)                | 3,650   | 18.3   | 3,220   | 27.7   |
| Cd (mg kg⁻¹)                | 3.82    | 15.7   | 1.77    | 36.3   |
| Cr (mg kg⁻¹)                | 7.32    | 16.1   | 17.4    | 21.0   |
| Cu (mg kg⁻¹)                | 25.0    | 22.9   | 155     | 27.4   |
| Fe (mg kg⁻¹)                | 24,700  | 28.1   | 3,950   | 8.83   |
| Mn (mg kg⁻¹)                | 33,100  | 12.8   | 1.0     | 2.1    |
| Ni (mg kg⁻¹)                | 0.75    | 8.9    | 41.5    | 17.9   |
| Pb (mg kg⁻¹)                | 3.38    | 15.4   | 9.99    | 15.8   |
| Zn (mg kg⁻¹)                | 1.1     | 18.1   | 59.0    | 22.9   |
| S (mg kg⁻¹)                 | 846     | 16.7   | 900     | 15.6   |
| Low heating value (kcal kg⁻¹) | 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(%) | Average | RSD(%) | Average | RSD(%) |
| O₂ (%)                      | 8.3     | 6.3    | 6.5     | 8.5    | –       |        | –       |        |
| CO₂ (%)                     | 11.5    | 4.5    | 12.4    | 5.4    | –       |        | –       |        |
| CO (ppm)                    | 45      | 10.1   | 35      | 17.4   | 350     |        |        |        |
| NO₃ (ppm)                   | 160     | 18.5   | 120     | 12.3   | 220     |        |        |        |
| SO₂ (ppm)                   | 14      | 15.7   | 19      | 11.4   | 220     |        |        |        |
| Particulate (mg Nm⁻³)       | 5.0     | 16.7   | 2.0     | 20.4   | 80      |        |        |        |
| PCDD/Fs (ng I-TEQ Nm⁻³)     | 0.0102  | 25.8   | 0.003   | 33.3   | 0.5     |        |        |        |
| Cd (mg Nm⁻³)                | 0.00134 | 18.4   | 0.00128 | 17.7   | 0.04    |        |        |        |
| Cr (mg Nm⁻³)                | 0.0147  | 12.6   | 0.0128  | 13.6   | –       |        |        |        |
| Cu (mg Nm⁻³)                | 0.00271 | 11.5   | 0.00133 | 22.4   | –       |        |        |        |
| Hg (mg Nm⁻³)                | 0.00021 | 10.8   | 0.00015 | 18.5   | 0.05    |        |        |        |
| Ni (mg Nm⁻³)                | 0.00317 | 13.4   | 0.00656 | 21.1   | –       |        |        |        |
| Pb (mg Nm⁻³)                | 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 [SO₂] 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 [NO₃] 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 [O₂] in Group II was further reduced to 6.5%, and thus, the formation of thermal NO₃ was partly reduced (see Eq. (2)).

\[
N_2 + O_2 \rightarrow 2NO \quad (2)
\]

When the coal was replaced with SRF, the PCDD/F concentrations in the flue gas were reduced from 0.01 ng I-TEQ Nm⁻³ (Group II) to 0.003 ng I-TEQ Nm⁻³ (Group I), which were both much lower than the regulated standard (0.5 ng I-TEQ Nm⁻³). 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⁻¹) and fly ashes (0.0003 ng I-TEQ g⁻¹) in Group II were slightly lower than those (0.0049 ng I-TEQ g⁻¹ and 0.0005 ng I-TEQ g⁻¹) 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⁻¹) (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 1,2,3,4,6,7,8-HpCDF (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⁻¹. 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⁻¹. 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 O₂ 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,
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⁻¹) | Bottom ash (%) | Fly ashes (%) | Flue gas (%) | Emission factor (mg ton⁻¹) |
| PCDD/Fs | 21.02 | 61.8 | 17.2 | 388 ng I-TEQ ton⁻¹ | 16.8 | 75.4 | 7.8 | 232 ng I-TEQ ton⁻¹ |
| 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–1).

| 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 Bottom ash | Group I Fly ash | Group II Bottom ash | Group II Fly ash |
|-------|--------------------|-----------------|---------------------|------------------|
| Al₂O₃ | 28.7               | 21.4            | 26.6                | 20.88            |
| CaO   | 0.572              | 4.17            | 0.997               | 5.88             |
| Fe₂O₃ | 2.17               | 4.87            | 3.23                | 5.45             |
| SiO₂  | 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, SiO₂ accounted for 64.1% and 65.8% in groups I and II, respectively. Next to SiO₂, the fractions of Al₂O₃ were 28.7% and 26.6% in Groups I and II, respectively. The percentages of Fe₂O₃ and CaO were both less than 5%. For the fly ashes, SiO₂ was still the main oxide in both Groups I (50.84%) and II (43.45%), and Al₂O₃ was also the secondary oxide in Groups I (21.4%) and II (20.88%). The percentages of CaO and Fe₂O₃ were all approximately 5%. For recycling as the raw materials in cement, the total Al₂O₃, CaO, Fe₂O₃, and SiO₂ 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⁻¹ 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⁻¹. The cost of the additives for SRF, including wood dust, bentonite, and coal ash was 50, 100, and -20 USD ton⁻¹, respectively. The price at which it was sold to the cogeneration plant was 30 USD ton⁻¹, 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⁻¹. The net revenue for recovering 1 ton of waste lubricant was 119 USD ton⁻¹. The capacity of this treatment plant was 30 tons day⁻¹, 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⁻¹) was approximately equal to that of coal (5,340 kcal kg⁻¹), but the price was about half (32 USD ton⁻¹) that of coal (60 USD ton⁻¹). The capacity of the cogeneration plant was 2 tons coal feeding per hour, where with a 50% replacement of coal
with SRF, it was 1 ton hr⁻¹. 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 [NOₓ].
2. In the scenario where 40% of the coal was replaced with SRF, the concentrations of NOₓ 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⁻¹ 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.

### REFERENCES

Arena, U., Mastellone, M.L., Perugini, F. (2003). The environmental performance of alternative solid waste management options. Chem. Eng. J. 96, 207–222. https://doi.org/10.1016/j.cej.2003.08.019

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. Waste Manage. 32, 625–639. https://doi.org/10.1016/j.wasman.2011.09.025

Azapagic, A., Perdan, S., Clift, R. (2004). Sustainable development in practice. J. Wiley & Sons. Ltd., Chicester, UK.

Chang, C.J., Yang, H.H. (2020). Impact on eye health regarding gaseous and particulate pollutants. Aerosol Air Qual. Res. 20, 1695–1699. https://doi.org/10.4209/aaqr.2020.03.0098

Chang, N.B., Wang, H.P., Huang, W.L., Lin, K.S. (1999). The assessment of reuse potential for municipal solid waste and refuse-derived fuel incineration ashes. Resour. Conserv. Recycl. 25, 255–270. https://doi.org/10.1016/S0921-3449(98)00066-4

Chen, S., Cui, K., Zhao, Y., Yin, Z., Chao, H.R., Chang-Chien, G.P. (2018). Sensitivity analysis of
atmospheric PM_{2.5}-bound content and dry deposition of total PCDD/Fs-TEQ: In the case of Xiamen and Zhangzhou, China. Aerosol Air Qual. Res. 18, 3096–3114. https://doi.org/10.4209/aaqr.2018.11.0393

Chen, T., Sun, C., Wang, T., Zhan, M., Li, X., Lu, S., Yan, J. (2020). Removal of PCDD/Fs and CBzs by different air pollution control devices in MSWIs. Aerosol Air Qual. Res. 20, 2260–2272. https://doi.org/10.4209/aaqr.2019.10.0536

Consonni, S., Giugliano, M., Grosso, M. (2005). Alternative strategies for energy recovery from municipal solid waste. Part A: Mass and energy balances. Waste Manage. 25, 123–135. https://doi.org/10.1016/j.wasman.2004.09.007

Directive 2008/98/EC of the European Parliament and of the Council on Waste and Repealing Certain Directives – Annex II, 19 November 2008.

Gug, J., Cacciola, D., Sobkowski, M.J. (2015). Processing and properties of a solid energy fuel from municipal solid waste (MSW) and recycled plastics. Waste Manage. 35, 283–292. https://doi.org/10.1016/j.wasman.2014.09.031

Kuo, Y.M., Wang, Y.K., Lin, S.L., Yin, L.T., Hsieh, Y.K. (2019). Air Pollution characteristics of reclaimation of refuse derived fuel (RDF) recovered from cutting oil waste. Aerosol Air Qual. Res. 19, 2576–2584. https://doi.org/10.4209/aaqr.2019.09.0481

Leme, M.M.V., Rocha, M.H., Lora, E.E.S., Venturini, O.J., Lopes, B.M., Ferreira, C.H. (2014). Techno-economic analysis and environmental impact assessment of energy recovery from municipal solid waste (MSW) in Brazil. Resour. Conserv. Recycl. 87, 8–20. https://doi.org/10.1016/j.resconrec.2014.03.003

Lombardi, L., Carnevale, E., Corti, A. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. Waste Manage. 37, 26–44. https://doi.org/10.1016/j.wasman.2014.11.010

Murer, M.J., Spliethoff, H., De Waal, C.M.W., Wilpshaar, S., Berkhout, B., Van Berlo, M.A.J., Gohlke, O., Martin, J.J.E. (2011). High efficient waste-to-energy in Amsterdam: Getting ready for the next steps. Waste Manage. Res. 29, 20–29. https://doi.org/10.1177/0734242X11413334

Myrin, E.S., Persson, P.E., Jansson, S. (2014). The influence of food waste on dioxin formation during incineration of refuse-derived fuels. Fuel 132, 165–169. https://doi.org/10.1016/j.fuel.2014.04.083

Nam-Chol, O., Kim, W.G. (2017). Investigation of characterization of municipal solid waste for refused-derived fuel, a case study. Energy Sources Part A 39, 1671–1678. https://doi.org/10.1080/15567036.2017.1367869

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J. (2015). Mass, energy and material balances of SRF production process. Part 3: Solid recovered fuel produced from municipal solid waste. Waste Manage. Res. 33, 146–156. https://doi.org/10.1017/S0734242X14563375

Psomopoulos, C.S., Bourka, A., Themelis, N.J. (2009). Waste-to-energy: A review of the status and benefits in USA. Waste Manage. 29, 1718–1724. https://doi.org/10.1016/j.wasman.2008.11.020

Qiu, J., Tang, M., Peng, Y., Lu, S., Li, X., Yan, J. (2020). Characteristics of PCDD/Fs in flue gas from MSWIs and HWIs: Emission levels, profiles and environmental influence. Aerosol Air Qual. Res. 20, 2085–2097. https://doi.org/10.4209/aaqr.2019.11.0610

Rada, E.C., Andreottola, G. (2012). RDF/SRF: which perspective for its future in the EU. Waste Manage. 32, 1059–1060. https://doi.org/10.1016/j.wasman.2012.02.017

Taiwan Environmental Protection Administration (TEPA) (2006). Standard Method of Detection of Heavy Metals in Outlet Line; NIEA A302.72C; Taiwan Environmental Protection Administration, Taiwan.

Taiwan Environmental Protection Administration (TEPA) (2010). Standard Sampling Method for PCDD/Fs of Flue Gas; NIEA A807.75C. Taiwan Environmental Protection Administration, Taiwan.

Taiwan Environmental Protection Administration (TEPA) (2014). Standard Method for Analyzing Heavy Metals in Extracts from Industrial Waste Acid Digestion with Microwave. NIEA R317.11C. Taiwan Environmental Protection Administration, Taiwan.

Taiwan Environmental Protection Administration (TEPA) (2015). Toxicity Characteristic Leaching Procedure; NIEA R201.15C. Taiwan Environmental Protection Administration, Taiwan.

Taiwan Environmental Protection Administration (TEPA) (2020a). Pollutants Emission Regulated Standards for Boilers. Taiwan Environmental Protection Administration, Taiwan.
Taiwan Environmental Protection Administration (TEPA) (2020b). Standards for Defining Hazardous Industrial Waste. Taiwan Environmental Protection Administration, Taiwan.

Tsai, J.H., Chen, S.J., Li, P.M., Chang-Chien, G.P., Huang, K.L., Tsai, C.H., Hsieh, C.Y., Lin, C.C. (2018). Characteristics of PM$_{2.5}$-bound PCDD/Fs, PCBs, PBDD/Fs and PBDEs from a diesel generator using waste cooking oil-based biodiesel blends. Aerosol Air Qual. Res. 18, 2583–2590. https://doi.org/10.4209/aaqr.2018.08.0310

Vermeulen, I., Caneghem, V.J., Block, C., Baeyens, J., Vandecasteele, C. (2011). Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals’ valorization. J. Hazard. Mater. 190, 8–27. https://doi.org/10.1016/j.jhazmat.2011.02.088

Wang, L.C., His, H.C., Wang, Y.F., Lin, S.L., Chang-Chien, G.P. (2010). Distribution of polybrominated diphenyl ethers (PBDEs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) in municipal solid waste incinerators. Environ. Pollut. 158, 1595–1602. https://doi.org/10.1016/j.envpol.2009.12.016

Yue, T., Wang, K., Wang, C., Tong, Y., Gao, J., Zhang, X., Zuo, P., Tong, L., Liang, Q. (2020). Emission characteristics of hazardous atmospheric pollutants from ultra-low emission coal-fired industrial boilers in China. Aerosol Air Qual. Res. 20, 877–888. https://doi.org/10.4209/aaqr.2019.10.0531

Zhou, C., Zhang, Q., Arnold, L., Yang, W., Blasiak, W. (2013). A study of the pyrolysis behaviors of pelletized recovered municipal solid waste fuels. Appl. Energy 107, 173–182. https://doi.org/10.1016/j.apenergy.2013.02.029