Characteristics of Fry-Drying and Solid Refuse Fuels for Organic Wastes with High Water Content

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ABSTRACT: With the dramatic increase in the quantity of organic wastes, economic and environmentally friendly technologies are urgently required for reducing the volume of sludge and remediating its harmful impacts. In this study, drying experiments were performed on sludge through fry-drying technology and the characteristics of the resulting fuels were investigated to identify proper methods for treating sewage sludge, wastewater sludge, swine excreta, and food waste and converting them into fuels. The four types of organic wastes were fry-dried, and the best drying conditions were found to be 140 °C for 8 min for sewage sludge and 150 °C for 10 min for wastewater sludge, swine excreta, and food waste. The water contents of sewage sludge, wastewater sludge, swine excreta, and food waste were 2.40 wt%, 2.70 wt%, 2.90 wt% and 5.82 wt%, respectively. Based on the results of fuel ratio, C/H ratio, thermogravimetric analysis (TGA), and derivative thermogravimetric (DTG) analysis on the four types of fry-dried solid refuse fuels, mixing the waste fuels with a certain proportion of coal for incineration in order to control the early ignition and rapid incineration rate was found to be effective.

KEYWORDS: Fry-drying, solid refuse fuels, organic sludge, food waste, swine excreta

1 INTRODUCTION

Since the 1970s, the South Korean economy has grown rapidly, bringing prosperity and improving living standards and the quality of life. The concentration of population around cities and the elevation of living standards have been accompanied by increasing mass production and mass consumption, leading to an increase of domestic sewage sludge and industrial wastewater sludge. In particular, the rise of meat and food consumption is causing a drastic augmentation of swine excreta and food waste [1].

Beginning in 2012, dumping sludge and food waste generated from sewage sludge and industrial wastewater sludge and swine excreta treatment plants into the ocean were gradually banned, and the dumping of wastes into the ocean was completely prohibited in 2016. Public treatment plants and contracted private facilities mainly rely on recycling and incineration to process the sewage sludge, wastewater sludge and swine excreta; however, these methods have limited capacity for treatment. Moreover, as the price of energy goes up, the cost of sludge treatment continues to increase. In order to reduce the cost of the installation and management of treatment plants, it is necessary to develop new treatment technologies along with installing more cost-effective facilities and reducing the volume of sludge sources. Food wastes are recycled as animal feed, compost, and biogas; however, an enormous amount of sludge is generated in the process at sewage water treatment plants. Because of the ban on dumping sludge into the ocean, a large amount of sludge has accumulated on land. Furthermore, the feed and compost recycled from food waste have not been widely accepted due to their high salinity and public misconception about them. Swine excreta are also recycled for compost and liquid fertilizer, but the strong odor is objectionable to consumers. In addition, the excessive antibiotics supplied in livestock farming remain in the compost and liquid compost, creating a risk of serious soil contamination [2, 3].

Recently, developed countries have been prioritizing the spreading of awareness about "zero emission" in sludge treatment. Along with this trend, recycling

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sludge for resources and fuel is gaining widespread attention from the public and various industries throughout Korean society. As ocean dumping has been banned, the Ministry of Environment needs to reform relevant regulations and policies on facility installation to promote the switch to inland waste treatment. Research is required on hazard evaluation, conventional recycling methods for treating wastes and recycling sludge on land in an environmentally friendly manner.

Methods for sludge treatment include landfilling, composting, recycling as fuel, consolidation, incineration, melting, and pyrolysis. Diverse methods are being developed and applied all over the world, and each country is adopting the most suitable solution given its unique circumstances, regional characteristics, societal and economic aspects, and environmental concerns.

Organic sludge consists of more than 75% water, so it is very important to dry the content in a preliminary stage before the actual treatment. Currently, agitation and rotary kiln devices are being used for drying organic sludge. Depending on drying targets and heat transfer methods, the indirect heat transfer method using conductive heat transfer and the direct hot air method using convective heat transfer can be employed [4–9]. However, these methods require a massive amount of energy, they are accompanied by the inevitable odorous gas, and the explosion risk is quite high. In addition, sludge drying methods using convective or conductive heat transfer involve high cost and long drying time due to their low energy efficiency. For this reason, an alternative technology is needed, and this study tested one promising technology, fry-drying, to process organic sludge and food wastes into solid fuels.

Fry-drying is a technology that evaporates a large amount of water from sewage sludge and wastewater sludge in a short period of time. It is possible to use the sludge for fuel if the calorific value is increased by reducing water content in the sludge [10–22]. To meet the demand for environmentally friendly treatment of organic waste and reduction of greenhouse gases, recycling of the final dried waste material for fuel is emerging as a means to discover new energy sources and new sludge treatment methods. Furthermore, the drying technology can be employed as a common process in recycling organic wastes and land treatment of sludge. Consequently, the quality of recycled products will be stabilized and economical storage and transport will be facilitated. If the water content in organic wastes and sludge is reduced below 10% while maintaining the organic matter, over 12,560 kJ of energy is generated and the sludge can be used in combination with coal in thermoelectric power plants. In particular, recycling organic wastes for fuel may be eligible for Clean Development Mechanism (CDM) project credits thanks to the international CO_2 emission trading scheme, which came into effect in 2015.

Unfortunately, some organic sludge has to be disposed of rather than burned due to the high drying cost and low heat content, which may cause secondary environmental contamination such as pollution of groundwater, surface water, soil and odor. In addition, it becomes more challenging to find new areas for landfills. Thus, recycling sludge and food wastes for fuel does not simply imply solving environmental problems only by disposing pollutants. In this light, the technology for sludge and food waste recycling can be another dimension that addresses the worldwide energy shortage and enables recirculation of resources [23–27].

The treatment and recycling of organic wastes is associated with several difficulties due to insufficient treatment options. As a response, this study investigated the fry-drying technology in order to find viable treatment and fuel recycling methods for sewage sludge, wastewater sludge, swine excreta, and food waste, which are generated in massive quantities. Technical analyses, including elementary analysis, calorific measurement, and fuel characteristics analysis, were performed before and after drying. In order to evaluate the efficiency and the stability of a drying machine and storability of dried fuel, changes in water content and moisture reabsorption rate were measured according to the drying time and temperature.

2 METHODS

2.1 Experimental Apparatus

The fry-drying system used in this study consists of rotational and continuous equipment. The rotational equipment is for identifying an optimum condition for each type of sludge by controlling types of sludge, drying temperature, and time. The continuous equipment is a pilot device that operates at 50 kg/h capacity, which is the optimum condition drawn from the rotational equipment. The oil temperature in the evaporation chamber was controlled between 140–150 °C and the temperature deviation was kept within ±3 °C during the experiment [10–13]. A computer was installed to monitor the evolution of the temperature and weight in real time. When the samples were added to oil, a mixture of vapor and oil was generated in a strong reaction with the oil and this oil was retrieved through a condenser.

Figure 1 shows the continuous system consisting of fry-drying equipment and a de-oiling machine.

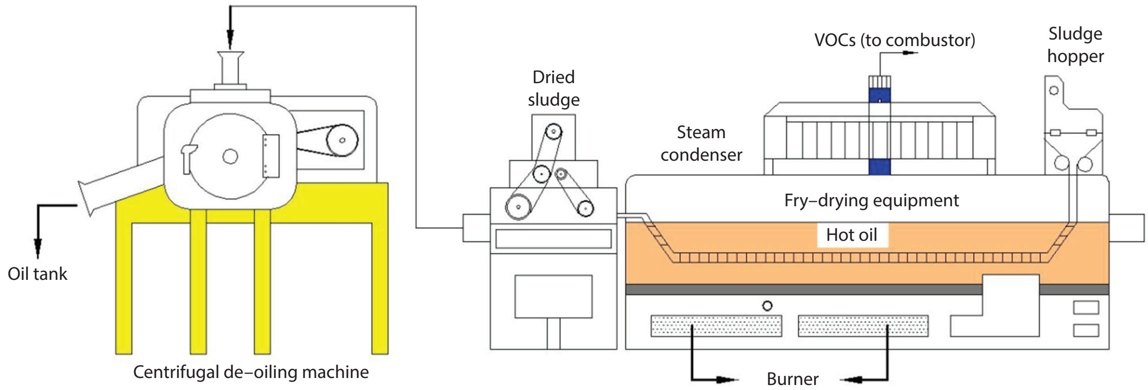

Figure 1 Schematic diagram of the continuous fry-drying system.

Table 1 Standard value of refined waste oil produced by two refining processes.

	Refined waste oil	
Components	**Ionic refining system**	**Vacuum distillation system**
Residual carbon (wt.%)	4.0 <	0.15 <
Water (wt.%)	1.0 <	0.5 <
Ash (wt.%)	1.0 <	0.05 <
Sulfur (wt.%)	0.55 <	0.2 <
Cd (mg/L)	1.0 <	1.0 <
Pb (mg/L)	30.0 <	1.0 <
Cr (mg/L)	5.0 <	1.0 <
As (mg/L)	2.0 <	1.0 <

The fry-drying equipment operates with a conveyor belt in a rotational mode. Sludge formed in specified thickness and size through the sludge hopper is supplied onto the conveyor belt and immersed in the oil. At this stage, the speed of sludge supply and the rotation speed of the conveyor belt are manipulated to control the length of time the sludge is kept in the oil, which is heated by a gas burner. The oil mist generated during the operation is collected in the condenser and moved to the oil-water separator. The oil is separated from water and reused, and the gas containing VOCs (volatile organic compounds) is moved to the burner for incineration. An oil separator operating at 10,000 rpm was used to separate and retrieve the oil, which was replaced by water in the dried sludge.

2.2 Experimental Samples and Refined Waste Oil

Sewage sludge, wastewater sludge, swine excreta, and food waste were selected as samples. The sewage sludge and swine excreta samples were collected after digestion and the food wastes were obtained from an apartment complex and they were arranged in a quadrat, and metal and vinyl materials were removed. The water contents of the samples were 72.18% (sewage sludge), 63.53% (wastewater sludge), 79.58% (swine excreta), and 80.64% (food waste).

Refined fuel oil, which is recycled from waste oil by removing water, ash, heavy metals, and other foreign materials, was used for fry-drying. It was prepared through chemical purification and vacuum distillation. In chemical purification, various cohesive agents containing anions are immersed in waste oil to allow the reaction of heavy metal substances in the oil and convert them into metallic salts of larger molecular masses, which are then deposited, separated, and dewatered to obtain refined oil. In vacuum distillation, waste oil input is heated by a heat medium boiler up to 110 °C to 150 °C and the water content is removed by allowing it to circulate through a heat exchanger, distiller, and separator. The remainder of sludge and ash content are removed in the centrifuge to finally produce refined oil. Table 1 shows the standard value of refined waste oil produced by two refining processes.

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In this study, the refined waste oil is produced by vacuum distillation system.

2.3 Experimental Methods

The purpose of the batch fry-drying experiment was to analyze the effects of changes in oil temperatures and drying time in order to draw the optimum temperature and time and to apply the result to the continuous operation system, considering the drying characteristics of sewage sludge, wastewater sludge, swine excreta, and food waste.

In the batch drying equipment, 1.0 L of refined fuel oil was poured into a square stainless container. When the heated oil reached a preset temperature, sludge samples of 50 g each were added and dried. The temperature was varied between 140 °C and 150 °C with drying times of 6, 8, 10, and 12 min. It was considered that the temperature dramatically falls when a sample with abundant water content reacts with the refined fuel oil, and more attention was paid to this during the experiment. The optimum fry-drying conditions for the samples could be determined through an analysis of water content evolution depending on the reaction condition. A drying experiment was conducted using the continuous drying equipment with the optimum oil temperatures and drying times drawn from the batch experiment.

2.4 Analysis Methods

Technical analysis (water content, ash content, volatile matter, and fixed carbon), elementary analysis, and heavy metal analysis were conducted and the calorific value was measured for the four fry-dried samples. A TGA-701 Proximate Analyzer (LECO Corp., USA) and a 1112 Elemental Analyzer (Thermo Fisher Scientific, UK) were used for the technical and elementary (C, H, N, S, and O) analyses, respectively. A TGA/SDTA 851e thermal gravimetric analyzer (Mettler Toledo, USA) and iCAP 6000 emission spectrometer (Thermo Elemental, U.K) were used for the TGA/DTG and heavy metal analyses (Hg, Cd, Cr, Pb, As, and Cu) respectively. The calorific value was measured with a calorimeter (Parr 1261 EA).

3 RESULTS

3.1 Results of Fry-Drying Experiment

In the fry-drying experiment, the time variation of water content was analyzed at drying temperatures of 140 °C and 150 °C. Figure 2 shows the change in water content after fry-drying for various durations at an oil temperature of 140 °C. After 6 min of drying time, all samples other than sewage sludge still had more than 5% of moisture content, and all samples other than food waste showed less than 5% of moisture content in 8 min. After 10 min of drying, sewage sludge, wastewater sludge, swine excreta, and food waste contained 2.4%, 4.1%, 4.8%, and 7.0% of water content, respectively, and after 12 min, no significant difference was observed in the amount of water content. Figure 3 shows changes in water content after fry-drying for various drying times at an oil temperature of 150 °C.

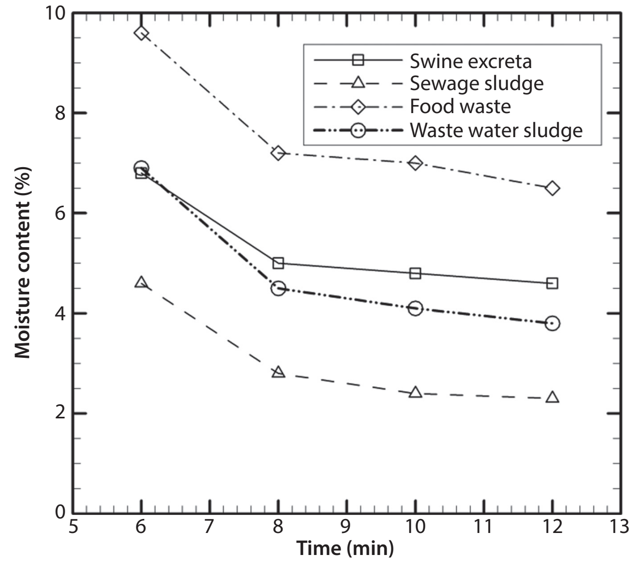

Figure 2 Moisture content curve for various fry-drying times (oil temperature: 140 °C).

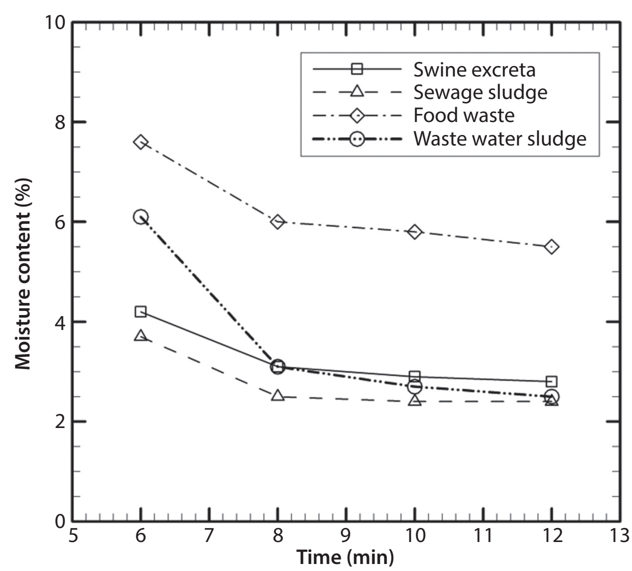

Figure 3 Moisture content curve for various fry-drying times (oil temperature: 150 °C).

In contrast to drying at 140 °C, all samples other than food waste showed water content below 5% at the oil temperature of 150 °C after 6 min of drying time. At 10 min, the water content in sewage sludge, wastewater sludge, swine excreta, and food waste was 2.4%, 2.7%, 2.9%, and 5.8%, respectively.

The first stage of the chemical evolution of the fry-drying process is a phase when heat transfer occurs due to the convection from the refined oil to the sludge, as the surface of the target substance is heated up at the initial temperature. Heat transfer occurs within a very short time and barely any water evaporation occurs. The second stage is a phase when free water evaporates from the sludge surface, which becomes crusty. The third stage takes the longest time in the entire fry-drying process and occurs when water evaporation is the most active, as the temperature of water in the central part of the sludge reaches the boiling point. As the water content decreased to 2%, little water evaporation occurred. We concluded that the optimum condition for sewage sludge is 140 °C for 8 min, and that for wastewater sludge, swine excreta, and food waste is 150 °C for 10 min.

An experiment on moisture reabsorption was conducted to study the amount of water absorbed back into the previously dried samples. This reabsorption experiment is highly important as dried sludge is often kept in open air or exposed to moisture during transportation. Changes in moisture content were observed throughout a period of two weeks at temperatures ranging between 24 °C and 28 °C and humidity between 73 and 75%. Swine excreta and food waste started to decompose during the water absorption experiment; therefore, the experiment was terminated in 7 days. Figure 4 shows the moisture curve of dried samples of sewage sludge, wastewater sludge, swine excreta, and food waste in the water reabsorption experiment. Water content increased from 2% at the beginning of the experiment to over 7% on the 4th day. On the 10th day it increased to 8.6% and this remained the same until the 14th day. The water absorption rate is believed to have been low as the surface of sample was coated with the oil from fry-drying. These materials can be used as solid fuels as the water content did not exceed 10% after 2 weeks of storage. The water content of swine excreta and food waste increased to 9.8% and 10.8%, respectively, on the 7th day and the experiment was ended early due to the presence of fungi and the development of decomposition.

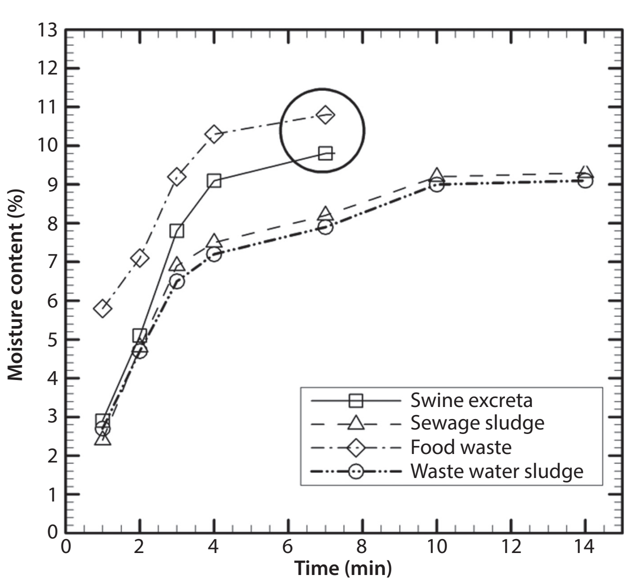

Figure 4 Moisture content reabsorption curve.

3.2 Results of Analysis

Table 2 and Table 3 show the results of the technical and elementary analysis on the original and fry-dried samples of the four types of sludge. Technical analysis was performed before and after drying using a TGA-701 Proximate Analyzer (LECO Corp., USA). Elementary analysis was performed before and after drying using a 1112 Elemental Analyzer (Thermo Fisher Scientific, UK). Water content of sewage sludge, wastewater sludge, swine excreta and food waste before drying was 72.18%, 63.53%, 79.58% and 80.64%, respectively, and that of wastewater sludge was the lowest among the four. Fixed carbon was 1.86% in food waste and 1.89% in sewage sludge and the other two samples recorded almost 0%. From the results of the four types of samples fry-dried at 150 °C for 10 min, it was found that generally the water content decreased and volatile matter largely increased. There was almost no change in fixed carbon and the content of volatile matter increased as water content declined. The water content of swine excreta, sewage sludge, food waste, and wastewater sludge was 2.90 wt%, 2.40 wt%, 5.82 wt%, and 2.70 wt%, respectively. Therefore, it was concluded that they were well dried below 5 wt% except for food waste.

The proportion of volatile matter significantly increased as oil substituted evaporated water, and food waste showed the highest rate of 88.74 wt%. Low calorific values were measured before and after drying. However, values under 8,300 kJ/kg were not measured because the equipment had several limitations. Low heating values before drying were not measured as the water content was high and there was very little fixed carbon. After drying, the low heating value of sewage sludge was the highest (19,975 kJ/kg) and that of swine excreta was the lowest (16,555 kJ/kg). As a result, using the fry-drying technology, a large amount of water was removed from the sludge in a short period of time and the volatile matter increased

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Table 2 Results of proximate analysis of four samples.

Components		Water (wt.%)	Volatile matter (w.t%)	Ash (wt.%)	Fixed carbon (wt.%)	Fuel ratio (FC/VM)	Low heating value (kJ/kg-wet)
Swine excreta	Before drying	79.58	15.02	5.24	0.16	0.01	–
	After drying	2.90	82.86	12.97	0.77	0.01	16,555
Sewage sludge	Before drying	72.18	14.70	11.23	1.89	0.13	–
	After drying	2.40	74.64	20.13	2.24	0.03	19,975
Food waste	Before drying	80.64	14.71	2.79	1.86	0.13	–
	After drying	5.82	88.74	4.15	1.29	0.01	18,074
Waste water sludge	Before drying	63.53	11.54	23.99	0.94	0.08	–
	After drying	2.70	57.47	38.85	0.98	0.02	16,973

Table 3 Results of ultimate analysis of four samples.

Components		C (wt.%)	H (wt.%)	N (wt.%)	0 (wt.%)	S (wt.%)	C/H
Swine excreta	Before drying	W	5.76	5.22	62.55	1.19	4.39
	After drying	53.57	9.17	2.56	34.08	0.62	5.84
Sewage sludge	Before drying	25.27	5.76	5.29	62.49	1.19	4.39
	After drying	54.70	9.46	4.75	30.18	0.31	5.78
Food waste	Before drying	49.71	6.71	4.82	38.76	0.00	7.41
	After drying	51.01	7.72	2.61	38.30	0.36	6.61
Waste-water sludge	Before drying	23.26	5.69	6.54	64.51	0	4.09
	After drying	55.15	8.57	1.98	34.30	0	6.44

considerably as the oil replaced the evaporated water and the heating value significantly increased as well. As shown in Table 2, the ratio of fixed carbon to volatile matter (FC/VM), which is the difference between fuel ratios, was not large as it was 0.01–0.13 before fry-drying and 0.01–0.08 after the process. In Table 3, the C/H ratio of all samples except for food waste increased from 4.09–7.41 before fry-drying to 5.78–6.61 after fry-drying. Soot generated during incineration may increase if the C/H ratio is higher in the solid fuel. In general, the fuel ratios of anthracite and lignite are 12 and below 1, respectively, and the C/H ratios of coal and gaseous fuel are 10–30 and approximately 3, respectively. The fuel ratios of the four types of samples were very low (>1.0) after fry-drying and the C/H ratios were also low (>10.0). The fuel ratio and C/H ratio of organic waste and sludge are low because all four sludge samples contain a large amount of volatile compounds without any significant fixed carbon. For this reason, fry-dried wastes are characterized by early ignition and a shorter length of burning time during incineration. Therefore, it is possible to compensate for the unwanted characteristics observed in burning fry-dried wastes by mixing them in an appropriate ratio with coal, which takes relatively longer in ignition and incineration.

Table 4 shows the results of the heavy metal analysis, which was performed after drying using an inductively coupled plasma atomic emission spectrometer (iCAP 6000, Thermo Elemental, UK). The proximate analysis of solid refuse fuel products was employed considering the following elements: Hg, As, Cd, Cr, Cu, and Pb. Hg was not found in any of the four samples; 162.2 mg/kg of Cu was detected in swine excreta, and 211 mg/kg of Cu and 52 mg/kg of Pb were detected in sewage sludge. The heavy metals found in fry-dried sewage, swine excreta, and food waste sludge

Table 4 Heavy metal analysis after fry-drying of four samples and Standard for solid refuse fuel (mg/kg).

Components	Hg	As	Cd	Cr	Cu	Pb
Swine excreta	ND	ND	ND	ND	162.2	ND
Sewage sludge	ND	ND	1	2	211	52
Food waste	ND	ND	ND	0.78	0.8	9
Waste water sludge	ND	105	ND	9,541	–	260
Standard for solid refuse fuel	1.2	13.0	9.0	–	–	200.0

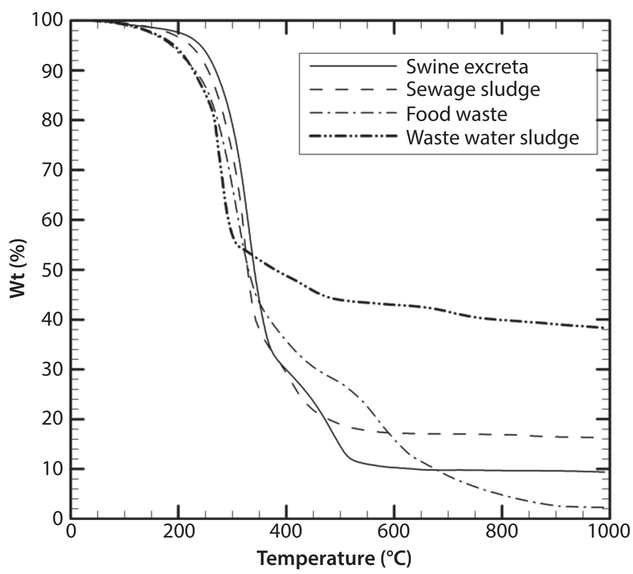

Figure 5 Thermogravimetric analysis curve of four samples (heating rate: 10 °C/min, carrier gas: air).

were below the limit in the environmental standards; therefore, they can be used as solid fuels. On the contrary, the amount of As, Cr, and Pb in the wastewater sludge was higher than the specified limit of the solid fuel standards in Korea; therefore, it cannot be used as a solid fuel. The Cr, As, and Pb concentration was very high in wastewater sludge because the sample was taken from a plating plant.

Figure 5 shows the results of thermogravimetric analysis (TGA), which was performed using a TGA/SDTA 851e thermal gravimetric analyzer (Mettler Toledo, USA). TGA analysis is used to measure the variation of sample weight according to temperature increase. In order to investigate the characteristics of combustion for fry-dried sludge, air was supplied via carrier gas and the rate of temperature increase was set at 10 °C/min to 1,000 °C [28, 29]. The initial reaction was evaporation of surface water and free water of the sludge until the temperature reached 100 °C. Most of the water content evaporated in this phase. When the temperature reached 200 °C, the evaporation of bound water inside the sludge samples was completed. Almost no change was observed in the weight of the sludge samples up to 200 °C because the successful fry-drying led to very low water content. When the water evaporation was complete, polymer dissociation started in the sludge. The weight drastically decreased at temperatures of 200~400 °C due to the depolymerization of the polymer substances in the sludge and incineration of volatile compounds. There was almost no weight reduction after 350 °C and 400 °C in wastewater sludge and sewage sludge, respectively, as decomposition was almost complete. In the case of food waste, the decomposition reaction lasted beyond 400 °C and the weight decreased up until 800 °C. The decomposition process of swine excreta also continued until 400 °C and the weight decreased to 500 °C. The decomposition of swine excreta and food waste continued to a high temperature because incineration continues to high temperatures if the substances contain little amount of ash and ample organic compounds.

Figure 6 shows the results of a derivative thermogravimetric analysis (DTG) for the four fry-dried samples. The DTG curves demonstrated the rate of weight decrease of each sample corresponding to the temperature, making it possible to determine the characteristics of samples in the incineration reaction. A low peak of the DTG curve indicates that the decline in weight is small, and a high peak indicates that it is large in the corresponding temperature per set time period. In the DTG results, the peak appeared at approximately 200 °C to 400 °C because the weight loss of the oil and volatile compounds, which replaced the water content inside the samples, was considerably large due to a combustion reaction. Wastewater sludge itself does not contain much organic matter and the peak temperature for this type of sludge is lower than other sludge types; after 300 °C, the weight barely decreased. Swine excreta and food waste, which contain an abundant amount of organic matter, show a peak rate of weight loss between 400 °C and 600 °C because of the combustion of organic matter.

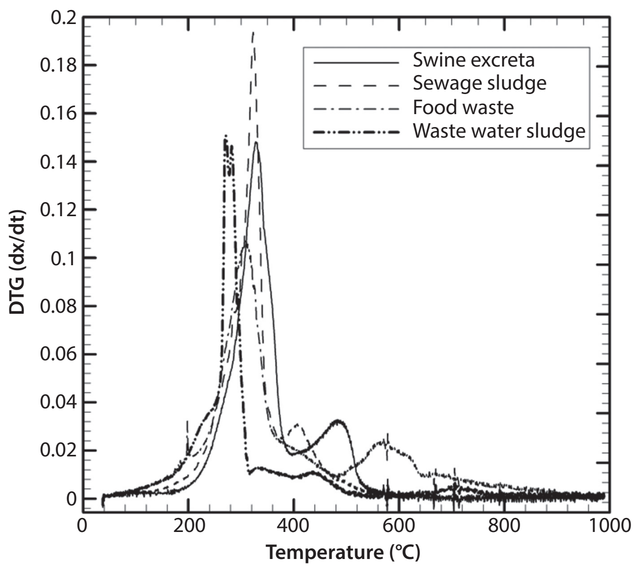

Figure 6 Derivative thermogravimetric analysis curve of four samples (heating rate: 10 °C/min, carrier gas: air).

4 CONCLUSION

A set of experiments were conducted on four typical types of organic wastes (swine excreta, sewage sludge, food waste, and wastewater sludge) using the fry-drying method in order to evaluate the efficiency of the drying system and the characteristics of dried substances. The following results were obtained:

1. The optimum drying conditions for the four types of sludge samples were found to be 140 °C for 8 min for sewage sludge, and 150 °C for 10 min for wastewater sludge, swine excreta, and food waste. Under these conditions, the water contents of swine excreta, sewage sludge, food waste, and wastewater sludge were 2.90 wt%, 2.40 wt%, 5.82 wt%, and 2.70 wt% respectively, and all three types of sludge were dried below 5 wt% except for the food waste.
2. The lower calorific values (LCVs) of the four samples before fry-drying could not be measured as the water content was very high, with a very small amount of fixed carbon. The LCV after the fry-drying was 16,555 kJ/kg for swine excreta, 19,975 kJ/kg for sewage sludge (the highest of the four samples), 18,074 kJ/kg for food waste, and 16,973 kJ/kg for wastewater sludge. The calorific values increased during the process because most of the water contained in the samples was replaced with heated oil.
3. The FC/VM of the four waste samples did not show much difference before fry-drying, where the ratio was 0.01–0.13, and after fry-drying, where the ratio was 0.01–0.08. The C/H ratio was 4.09–7.41 before the process and 5.78–6.61 after the process, and the ratio of the three types of samples showed an increase except for food waste. The fuel characteristics of the fry-dried waste fuels can be supplemented by mixing the fry-dried wastes with a certain proportion of coal, which has a relatively longer ignition time and burning duration compared to processed waste fuels.
4. In the heavy metal analysis, Hg was not found in any of the four samples; 162.2 mg/kg of Cu was detected in swine excreta, and 211 mg/kg of Cu and 52 mg/kg of Pb were detected in sewage sludge. The heavy metals found in fry-dried sewage, swine excreta, and food waste sludge were below the limit in the environmental standards; therefore, they can be used as solid fuels. On the contrary, the amount of As, Cr, and Pb in the wastewater sludge were higher than the specified limit of the solid fuel standards in Korea; therefore, it cannot be used as a solid fuel.
5. In the TGA and DTG curves of the four samples after fry-drying, a dramatic decline in weight was observed as volatile matter was gasified at temperatures between 200 °C and 400 °C. This peak occurred because oil replaced the evaporated water in the sludge samples during the fry-drying process. The reaction in wastewater and sewage sludge, which contain low amounts of organic matter, was almost completed at 400 °C and that in swine excreta and food waste, which contain high amounts of organic matter, continued up to higher temperatures.

The technology of drying sludge using typical technology with high water content to a water content of approximately 10% is always difficult because of the adhesive characteristics of sludge. Many methods have been applied, including direct and indirect heat drying, but these approaches of reducing water content to below 40% after drying are very inefficient in energy utilization of drying sludge because of low heat transfer coefficient of 75 ~ 140 W/m^2 °C. But the fry-drying technology has a high heat transfer coefficient of approximately 500 ~ 2,500 W/m^2 °C in drying sludge. In the fry-drying system, the heated oil rapidly evaporates the water contained in the sludge, leaving the oil itself. After approximately 10 min, the water content of the sludge was less than 10%, and its lower heating value surpassed 16,555 kJ/kg-wet.

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