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Experimental Study of the Fry-Drying Phenomena of Organic Wastes in Hot Oil for Waste-Derived Solid Fuel

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Abstract

In sludge treatment, drying sludge using typical technology with high water content to a water content of approximately 10% is always difficult because of adhesive characteristics of sludge in drying. 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. In this study, fry-drying technology with a high heat transfer coefficient of approximately 500 W/m²·˚C was used to dry swine excreta, sewage and industrial sludge. Also waste oil was used in the fry-drying process, and because the oil's boiling point is between 240˚C and 340˚C and the specific heat is approximately 60% of that of water. In the fry-drying system, the sludge is input by molding it into a designated form after heating the waste oil at temperatures between 130˚C and 150˚C. At these temperatures, the heated oil rapidly evaporates the water contained in the sludge, leaving the oil itself. After approximately 8 - 10 min, the water content of the sludge was less than 10%, and its heating value surpassed 20,000 kJ/kg. Indeed, this makes the organic sludge appropriate for use as a solid fuel. The dried swine excreta, sewage and industrial sludge can be used in an incinerator like low-rank coal or solid fuel.

Keywords

Swine Excreta, Sewage Sludge, Industrial Sludge, Fry-Drying Technology, Waste-Derived Solid Fuel

1. Introduction

Water contained in the sludge is categorized as follows: free water, surface water, interstitial water, and bound

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water. Free water and surface water are easily evaporated at 100˚C ± 5˚C, but the process of evaporating interstitial water and bound water requires temperatures upwards of 400˚C. Current drying technologies that are widely used include the convection heat transfer method, wherein gas is heated to between 400˚C and 600˚C to dry the sludge, and the heat conduction transfer method, which is an indirect heat transfer method that circulates high-temperature steam or gas inside heat transfer equipment while the wet sludge moves on the outside. Indeed, this process is also time-consuming, because as the outer surface of the sludge dry, more time is required (from 40 to 60 min) to decrease the water content to about 40%. Furthermore, as the surface of the sludge becomes hard, the speed of the process becomes remarkably slow. It can be seen that the sludge drying equipment currently used is inefficient with regard to energy and time, and in the end only partially dries the sludge.

The typical drying technologies of sludge have other serious obstacles such as a reduction in surface area, surface carbonation and solidification, fugitive dust, and the offensive odor of the heated gas. Compared to general material drying, sludge drying is a complicated process because the combination of bound water and interstitial water that exists inside the sludge shortens the constant rate drying period and lengthens the falling rate drying period.If dried organic sludge is to be used as a waste-derived solid fuel, its water content should be less than 10 wt.%, and its low heating value should be maintained at more than 12,560 kJ/kg (wet basis). Drying methods can be classified according to the mode of heat transfer: drying by conductive heat transfer (e.g., thin film drying) and drying by convective heat transfer with hot air or a combustion gas. However, these methods are subject to the risk of explosion and fire due to the presence of oxygen and volatile organic compounds from the sludge. They are generally costly and inefficient owing to the long drying time and low-efficiency energy use; moreover, odorous [1]-[6]. Therefore, the present research used evaporative drying by immersion in hot oil (EDIHO), also known as fry-drying, instead of conventional drying methods to transform sludge into fuel. The heat transfer coefficient of the boiling process is upward of 2500 $W/m^2\cdot{}^\circ C$, whereas the convective heat transfer coefficient is usually between 75 and 140 $W/m^2\cdot{}^\circ C$ [7] [8].

EDIHO achieves rapid drying by direct contact between water on the surface of the sludge and oil heated to 130˚C - 150˚C; vapour bubbles form, and boiling heat transfer occurs due to a strong warm current. Moreover, water in the sludge is displaced by oil through strong diffusion in the sludge, even in livestock sludge, which has high water content and strong cooking properties [9]-[12]. Various oils may be used in fry-drying, such as refined waste oil produced by refining waste oil from industrial settings, waste vegetable oil, and dissoluble animal oil, as well as all types of fuel oil. The present research investigated the drying process that occurs in fry-drying of livestock sludge, sewage sludge and industrial sludge using a refined waste oil and B-C heavy oil. The characteristics of the dried sludge were examined through thermo-gravimetric analysis to evaluate their suitability as a solid fuel.

2. Experimental Apparatus and Methods

2.1. Experiment Apparatus

Figure 1 shows the continuous-type fry-drying apparatus used for the present research. This system is divided into three parts: the first part consists of sludge feeding equipment, which inputs sludge to the evaporative drying tank. The sludge injector, which is operated by a variable-speed motor, pushes the sludge through five holes with 10 mm diameter. The second part is the sludge fry-drying tank where the supplied sludge is dried. The tank is 1.8 m in length, 1.2 m in height, and 1.0 m width, with a waterwheel type drum attached. Inside the drum, a screw feeder controls the fry-drying time of sludge. In order to increase the temperature of the waste oil inside the drying equipment, 10 kW electric coils and a gas burner are attached and a temperature controller is used to adjust the temperature of oil. The third part is the condenser, wherein steam, oil, and volatile organic compounds (VOCs) generated from the drying equipment that separated into condensed liquids and VOCs. And the condensed liquids are separated into water and oil at the oil-water separator. The separated oil is then transferred to the waste oil tank, and the condensed water is stored in the waste water tank. The VOCs and odorous gases are burnt after being transported to the burner through a tube by using an I.D. fan. The entire process, from the input of the sludge to the output of the finished product, takes about 10 min, and the equipment can treat 50 to 100 kg of sludge in 1 hour.

2.2. Experiment Samples and Oil

The results of proximate analysis (ASTM D3172, 3174, 3175) and ultimate analysis (EA1108, Fisons) for each

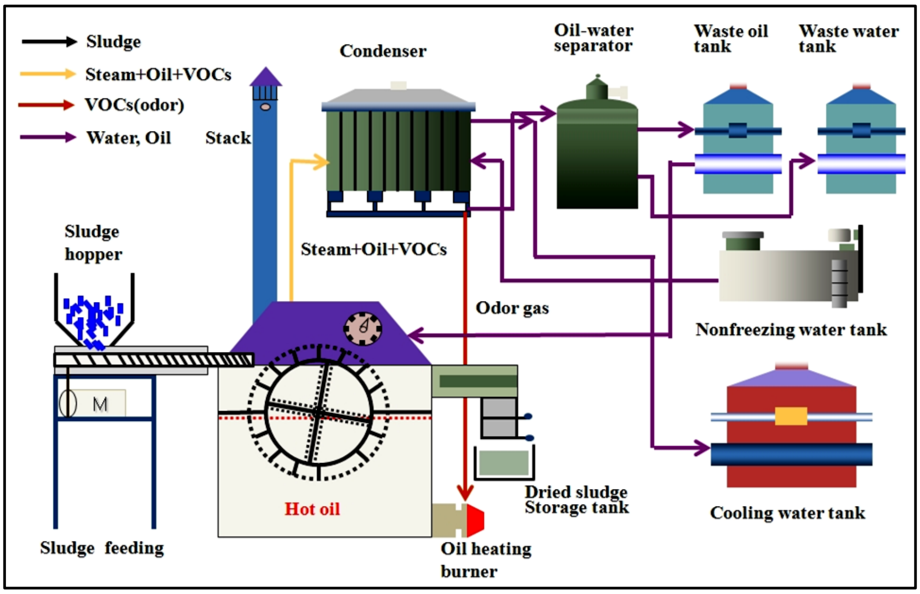

Figure 1. Schematic diagram of continuous-type fry drying system for organic waste.

sludge are shown in Table 1 and Table 2, respectively. The water content of the swine excreta is 78.90% before drying. The percentages of ash, fixed carbon, and volatile matter before drying were 4.76%, 0.23%, and 16.11%, respectively. And water content of the sewage and industrial sludge were 83.49%, 78.56%, respectively.

Refined waste oil from engine lubricants, cooling oil, and machine tool oil is produced by removing water, ash, heavy metals, and other foreign substances in order to reuse the waste oil as fuel oil. A chemical refinement process is used to produce refined waste oil; the process includes the production of metallic salts having a high molecular weight by reacting a component such as a heavy metal with anion-containing coagulants injected into the oil, followed by precipitation, separation, and dehydration. The waste oil thus treated was further processed into refined fuel oil as follows: the oil was heated at 110˚C - 150˚C by heating a media boiler; water in the heated waste oil was removed by circulating the oil through a heat exchanger, distiller, and classifier; and the remaining ash, and similar contaminants were removed from the resulting waste oil by using a decanter and a centrifuge. Table 3 shows the results of component analysis of refined waste oil produced by two refining processes. In this experiment, the refined waste oil has a boiling point of between 240˚C and 340˚C, and a specific heat of between 2.1 kJ/kg·˚C and 2.9 kJ/kg·˚C.

Heavy oil is highly cohesive, with a cohesive degree of greater than 50 cSt at 50˚C. Among the heavy oils, B-C heavy oil has the strongest cohesive property and is used to fuel large boilers and large, low-speed diesel engines and as a combustor installed with preheating equipment. It is the most widely used heavy oil in Korea. The qualities of heavy oils are classified internationally according to the viscosity range (viscosity at 50˚C), sulphur content, and other properties. The viscosity and sulphur content increase gradually as the grade changes from A to B to C. The sulphur content in B-C heavy oil for mass consumption is regulated because of problems such as air pollution in cities. Table 4 shows the quality standards of the different types of heavy oil.

2.3. Experiment of Fry-Drying Sludge

The parameters for fry-drying were the oil temperature, and drying time. We analysed the effect of each parameter on the water content after drying by varying them in the experiments. We selected 10 wt.% as the standard for water content after drying because that is the legal standard for solid fuel products in Korea. The drying experiments were performed at oil temperatures of 130˚C - 150˚C and drying times of 4 - 10 min. All experiments were repeated three times for each variable for accuracy; the results reported below are arithmetic means.

Figure 2 shows sewage sludge before and after fry-drying. Sludge was immersed in oil heated to a temperature much lower than its boiling point (approximately 340˚C), and from which heat was directly transferred to the sludge. With its surface exposed to the hot oil, heat was rapidly transferred into the sludge, facilitating the discharge and evaporation of bound and interstitial water. High temperature and activity of hot oil with smaller

Table 1. Proximate analysis of swine excreta, sewage and industrial sludge before fry-drying.

Samples \ Components	Water (wt.%)	Volatile matter (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Low heating value (kJ/kg-wet)	High heating value (kJ/kg-wet)
Swine excreta	78.90	16.11	4.76	0.23	422	4543
Sewage sludge	83.49	7.59	6.53	2.39	−1154	2434
Industrial sludge	78.56	4.87	16.33	0.24	−2867	704

Table 2. Ultimate analysis of swine excreta, sewage and industrial sludge before fry-drying.

Samples \ Elements	C (wt.%)	H (wt.%)	N (wt.%)	O (wt.%)	S (wt.%)	Cl (PPM)
Swine excreta	56.32	9.45	6.74	26.98	0.51	623.70
Sewage sludge	49.17	6.67	35.83	8.33	0	1.9
Industrial sludge	37.68	7.15	4.07	51.10	0	0

Table 3. Proximate analysis of swine excreta, sewage and industrial sludge after fry-drying.

Samples \ Components	Water (wt.%)	Volatile matter (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Low heating value (kJ/kg)	High heating value (kJ/kg)
Dried swine excreta with RO[a]	1.56	83.70	12.50	2.24	27,842	30,334
Dried swine excreta with BC[b]	1.62	81.84	12.32	4.22	28,169	30,567
Dried sewage sludge with RO[a]	2.99	69.64	22.13	5.24	26,445	29,296
Dried industrial sludge with RO[a]	1.96	57.29	40.75	0	19,238	22,018

[a]Refined waste oil; [b]B-C heavy oil.

Table 4. Ultimate analysis of swine excreta, sewage and industrial sludge after fry-drying.

Samples \ Elements	C (wt.%)	H (wt.%)	N (wt.%)	O (wt.%)	S (wt.%)	Cl (ppm)
Dried swine excreta with RO[a]	67.99	10.85	2.92	18.10	0.14	583.89
Dried swine excreta with BC[b]	70.44	10.22	2.62	16.52	0.20	469.34
Dried sewage sludge with RO[a]	41.69	8.21	3.62	23.46	0.23	0
Dried industrial sludge with RO[a]	71.08	12.15	1.09	15.69	0	0

[a]Refined waste oil; [b]B-C heavy oil.

Figure 2. Photography of before and after fry-drying sewage sludge.

specific heat compared to water increase the temperature of moisture in sludge, resulting in the increase of internal pressure caused by a steam evaporation phenomenon, and such increase maximizes the structure of internal pores, which plays a role to deliver materials between internal moisture. Accordingly, the increased moisture pressure and expansion of emission path issue the steam outside, and the negative pressure inside of the sludge which is formed temporarily makes smooth the influx of waste oil, maximizing the dry efficiency. We found that fry-drying reduced the water content of sludge from around 80% to 5%. In addition, analysis of dried sludge suggested that partial replacement of the evaporated moisture with oil is increased the heating value of the sludge.

Figure 3 shows the drying curve of sludge with an 83.49% water content that was evaporated in the fry-drying equipment with waste oil heated to 150˚C. In this figure, the constant rate drying period of the sludge lasted from 4 - 5 min. Generally the constant rate drying period is usually short, while the falling rate drying period is generally long when using other drying technologies such as direct and indirect heating system. But conversely the fry-drying process has the constant rate drying period is relatively long and the falling rate drying period is short due to high turbulent heat and mass transfer in the constant rate drying period. The final water content of the sludge dried for 8 min is 2.0%.

3. Results and discussion

3.1. Analysis of Sludge after Drying

3.1.1. Proximate and Ultimate Analyses

Table 3 and **Table 4** show the proximate and ultimate analyses of the swine excreta, sewage and industrial sludge after fry-drying for 10 min at 150˚C, the conditions that yielded the lowest water content after drying. The water content of swine excreta decreased from 78.90 wt.% before drying to 1.56 wt.% (refined waste oil) and 1.62 wt.% (B-C heavy oil). The water content of sewage sludge decreased from 83.49 wt.% before drying to 2.99 wt.% (refined waste oil), and industrial sludge decreased from 78.56 wt.% before drying to 1.96 wt.% (refined waste oil). The volatile matter content of swine excreta, sewage and industrial sludge before drying were 16.11 wt.%, 7.59wt.%, and 10.02 wt.%, respectively. After fry-drying, that of the swine excreta, sewage and industrial sludge increased to 83.70 wt.%, 69.64 wt.%, 57.29 wt.%, respectively. The reason is that the speed of fry-drying is fast because moisture is replaced with oil by strongly turbulent heat and mass transfer between oil and sludge, so oil uptake occurs. Thus, the presence of the oil greatly increased the volatile matter content. The low heating value (LHV) after fry-drying was swine excreta [27,842 kJ/kg (wet basis)], sewage sludge [26,445 kJ/kg (wet basis)], industrial sludge [19,238 kJ/kg (wet basis)], respectively.

3.1.2. Heavy Metal Analysis

The results of the heavy metal analysis of the three types of sludge are shown in **Table 5**. We also analysed the heavy metal content of the refined waste oil. The legal standard for heavy metal content in solid fuels prescribes the Pb, Cd, Hg, As, and Cr content; the standard is shown in **Table 5** for comparison. For this analysis, we used the IRIS DUO, an ICP (Inductively Coupled Plasma Emission Spectroscopy). We analyzed Hg, As, Cd, Cr,Pb and Al for each sample. The heavy metal content in the industrial sludge is as follows: Al, As, Cr, and Pb were detected in concentrations of 4395, 93, 4680, and 272 ppm, respectively. Hg and Cd were not detected. The heavy metal content in the sewage sludge is as follows: Al, Cd, Cr, and Pb were detected in concentrations of 16,250, 1, 34, and 72 ppm, respectively. Hg is not detected. In the case of the swine excreta, heavy metal elements of Al, is found in concentrations of 91 ppm. Hg, As, Cd, Cr, Pb were not detected. The concentration of aluminum was extremely high sewage and industrial sludge because ($MgAl(SO_4)_2 \cdot 12H_2O$) was used as a cohesive agent during the wastewater treatment process.

3.1.3. TG/DTG Analysis

Thermo-gravimetric analysis (TGA) is widely used to investigate the state change process and thermal stability of materials during heating. We used it first to understand the physical and chemical changes in the samples by observing their weight changes with heating; we also used it to understand various phenomena accompanying heating. **Figure 4** shows the results of TGA of swine excreta before and after drying at a heating rate of 10 ˚C/min with air as a carrier gas. As the temperature was increased from room temperature, a dramatic reduction in the swine excreta's weight occurred around 100˚C due to a reduction in their water content. In addition, emission

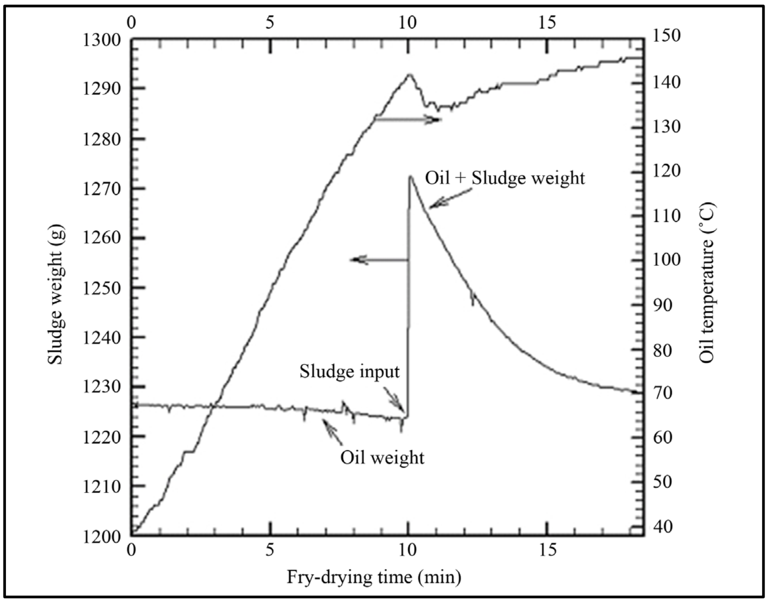

Figure 3. Drying curve of sludge in fry-drying equipment.

Table 5. Heavy metal content of swine excreta, sewage and industrial after fry-drying (mg/kg).

Samples \ Elements	Hg	Al	As	Cd	Cr	Pb
Dried swine excreta with RO[a]	ND	91.4	ND	ND	ND	ND
Dried swine excreta with BC[b]	ND	90.3	ND	ND	ND	ND
Dried sewage sludge with RO[a]	ND	16,250	ND	1	34	72
Dried industrial sludge with RO[a]	ND	4395	93	ND	4680	272
Standard for solid waste fuel	1.2	-	13.0	9.0	30.0	200.0
Refined waste oil	ND	47.0	ND	ND	1.0	8.0

[a]Refined waste oil; [b]B-C heavy oil.

and combustion of the initial volatile matter, carbon residue, and residual volatile matter occurred between 250˚C and 500˚C. Little reduction in the weight of the dried swine excreta appeared around 100˚C because their water content was low. The reaction during drying using B-C heavy oil is believed to occur gradually at temperatures of up to 560˚C because B-C heavy oil has many more components that can react at high temperature than the refined waste oil.

Differential thermo-gravimetric analysis (DTG) was performed by differentiating the TGA curves; the results are shown in **Figure 5**. The DTG curves show the speed at which the weight decreased in each sample according to temperature, so combustion features can be determined more clearly. Swine excreta before drying, peaks appeared around 100˚C; these represent moisture that was removed during drying. After fry-drying, the peak around 100˚C did not appear, because fry-drying decreased the water content. The peak around 300˚C was determined to be the result of a devolatilisation reaction.

For the swine excreta fry-dried in refined waste oil, the devolatilisation peak was much larger than that for the excreta fry-dried in B-C heavy oil, and the reaction temperature was slightly lower. The reason is that combustion of the volatile matter proceeded more rapidly in the refined waste oil than in the B-C heavy oil. The lower peak around 390˚C - 440˚C for the latter represents the combustion reaction of organic material having high molecular weight. For the B-C heavy oil, but not the refined waste oil, a DTG peak appeared around 510˚C owing to combustion of the char component of the B-C heavy oil. Differences in the number of peaks or the temperature at which they formed resulted from differences in the combustion features according to the oil component used for fry-drying.

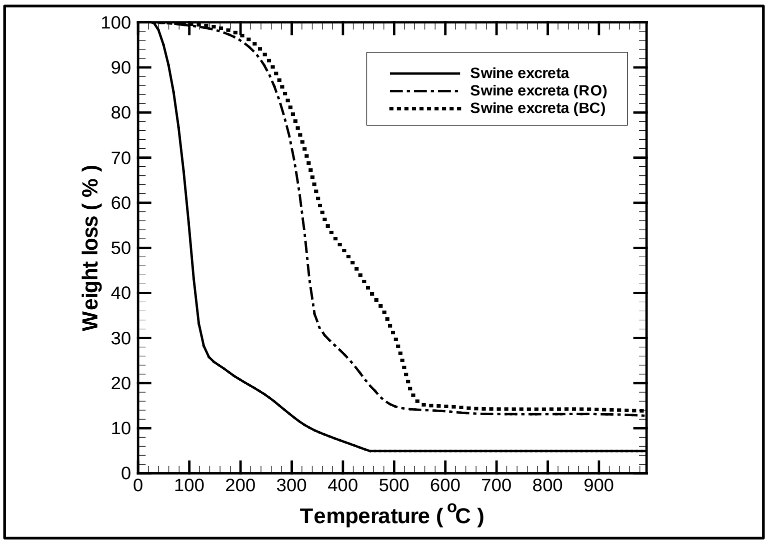

Figure 4. TGA curves of swine excreta (heating rate: 10˚C/min, air).

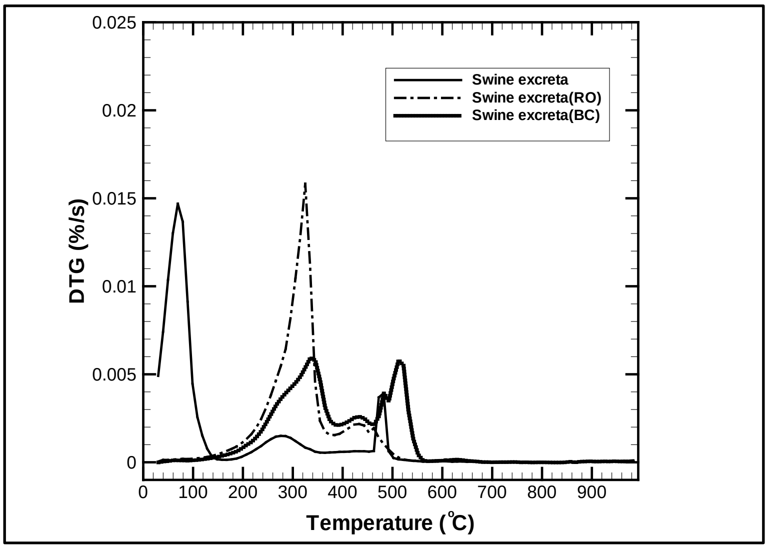

Figure 5. DTG curves of swine excreta (heating rate: 10˚C/min, air).

3.2. Results of Fry-Drying Experiment

Figure 6 shows the results of fry-drying of swine excreta having a water content of 78.90 wt.%. Refined waste oil (1 L) was used, 50 g of swine excreta were input, and the drying temperatures were 130˚C, 140˚C, and 150˚C. The most important parameters in fry-drying using oil are the oil temperature and drying time. Energy was required to increase the temperature, and much energy was consumed when the drying time was increased. Therefore, the water content after drying at a given temperature and drying time is crucial. Fry-drying at an oil temperature of 130˚C for longer than 8 min was ineffective, since the final water content was high (20 wt.%). However, drying at 140˚C for 4, 5, 6, 8 and 10 min yielded final water contents of 21.11 wt.%, 12.79 wt.%, 3.96 wt.%, 3.36 wt.% and 3.21 wt.%, respectively. Note that drying times of 6 min or more yielded water contents of less than 10 wt.%. Drying at 150˚C for 4, 5, 6, 8 and 10 min yielded final water contents of 12.33 wt.%, 3.66 wt.%, 1.66 wt.%, 1.56 wt.%, and 1.55 wt.%, respectively.

Figure 7 shows the results of fry-drying of raw swine excreta having a water content of 78.90 wt.%. B-C heavy oil (1 L) was used, 50 g of swine excreta were input, and the drying temperatures were 130˚C, 140˚C, and 150˚C. As in the experiment using refined oil, the drying was poor when drying at an oil temperature of 130˚C

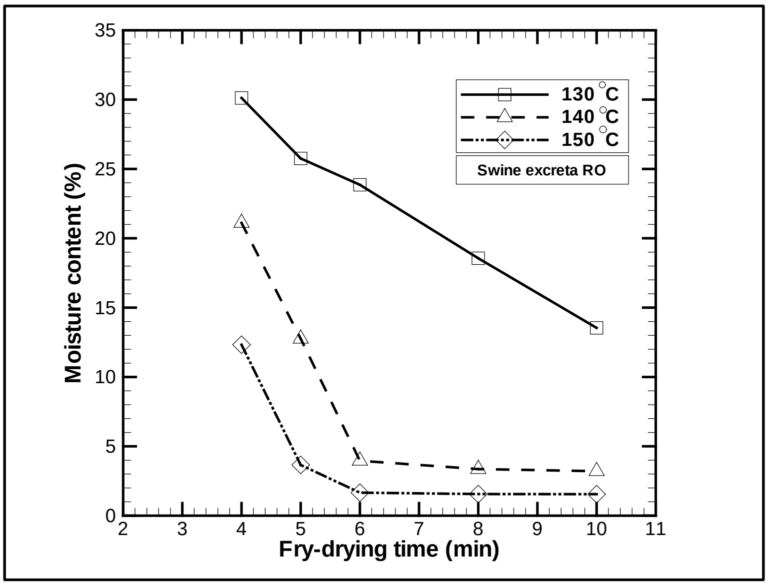

Figure 6. Drying curve for swine excreta dried in refined waste oil at various oil temperatures.

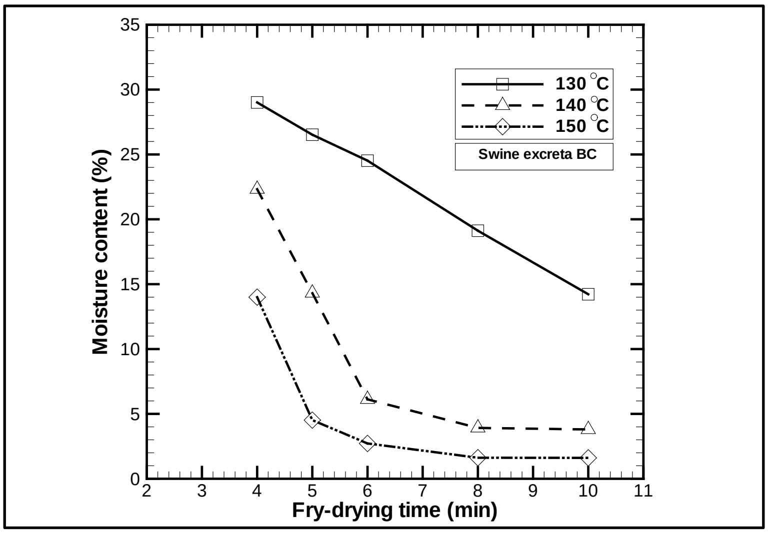

Figure 7. Drying curve of swine excreta dried in B-C heavy oil at various oil temperatures.

for 8 min (final water content of more than 20 wt.%). However, drying at 140˚C for 4, 5, 6, 8, and 10 min yielded final water contents of 22.32 wt.%, 14.32 wt.%, 6.12 wt.%, 3.92 wt.%, and 3.80 wt.%, respectively. Note that drying times of 6 min or longer yielded a water content of less than 10 wt.%. Drying at 150˚C for 4, 5, 6, 8, and 10 min yielded water contents of 14.00 wt.%, 4.52 wt.%, 2.72 wt.%, 1.62 wt.% and 1.61 wt.%, respectively. A comparison with the results for refined waste oil in **Figure 6** and **Figure 7** shows that the water content after drying varied slightly with the type of oil at shorter drying times, but no such difference in water content appeared when the drying time was long (>6 min).

Figure 8 shows the results of fry-drying of sewage sludge having a water content of 83.49 wt.%. Refined waste oil (1 L) was used and the drying temperatures were 130˚C, 140˚C, and 150˚C. Drying at 150˚C for 4, 5, 6, 8, and 10 min yielded water contents of 2.81 wt.%, 2.37 wt.%, 2.22 wt.%, 2.59 wt.% and 1.97 wt.%, respectively. **Figure 9** shows the results of fry-drying of industrial sludge having a water content of 83.49 wt.%. Refined waste oil (1 L) was used and the drying temperatures were 130˚C, 140˚C, and 150˚C. Drying at 150˚C for

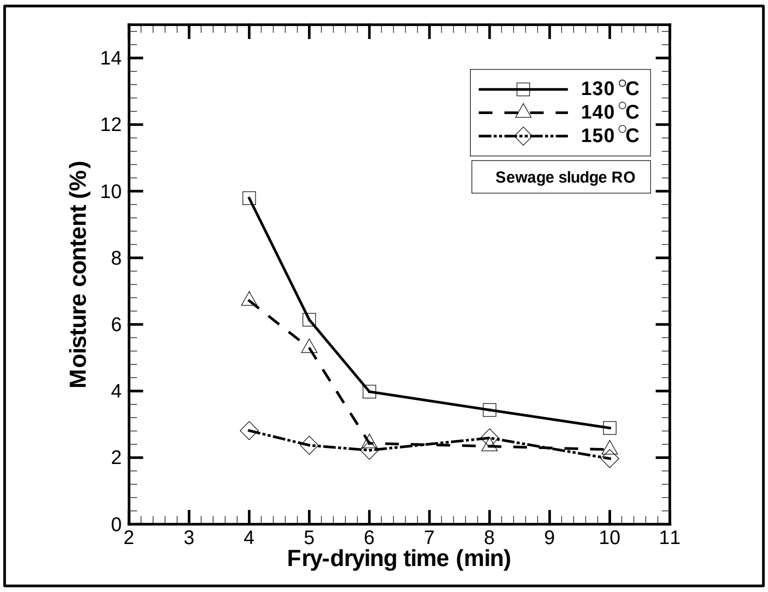

Figure 8. Drying curve for sewage sludge dried in refined waste oil at various oil temperatures.

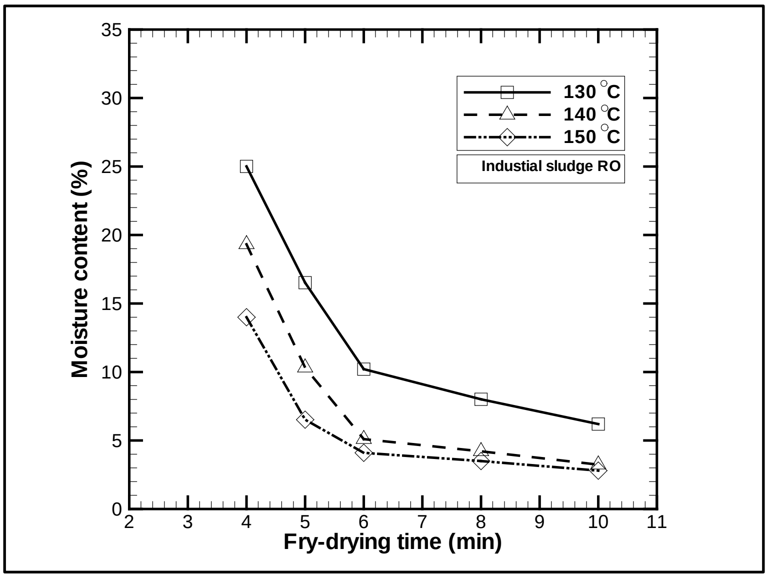

Figure 9. Drying curve for industrial sludge dried in refined waste oil at various oil temperatures.

4, 5, 6, 8, and 10 min yielded water contents of 13.95 wt.%, 6.52 wt.%, 4.10 wt.%, 3.50 wt.% and 2.80 wt.%, respectively.

4. Conclusions

We experimentally investigated the fuel characteristics and drying of swine excreta, sewage and industrial sludge treatment plant using fry-drying technology. We obtained the following results.

1) When swine excreta (water content: 78.90 wt.%) was dried at an oil temperature of 150˚C for 8 min, the resulting water contents were 1.56 wt.% (after drying in refined waste oil) and 1.62 wt.% (after drying in B-C heavy oil). Refined waste oil was slightly more effective at decreasing the water content than B-C heavy oil, but the difference was not significant.

2) When sewage sludge (water content: 83.49 wt.%) was dried at an oil temperature of 150˚C for 8 min, the resulting water contents were 2.59 wt.% (after drying in refined waste oil). And industrial sludge (water content: 78.56 wt.%) was dried at an oil temperature of 150˚C for 10 min, the resulting water contents were 2.80 wt.% (after drying in refined waste oil).

3) The low calorific values of swine excreta, sewage sludge and industrial sludge before drying were 422 kJ/kg, −1154 kJ/kg and −2867 kJ/kg, respectively, and those after drying at 150˚C for 8 - 10 min were 27,842, 26,445 kJ/kg and 19,238 kJ/kg, respectively, depending on the oil used; thus, the low calorific value increased greatly. The reason is that the water content decreased, and at the same time, moisture was replaced by oil during drying.

4) TGA revealed that emission of initial volatile matter, carbon residue, and residual volatile matter and combustion of fixed carbon occurred between atmospheric temperatures in the reactor of 250˚C and 500˚C when air was used as the transfer gas. Therefore, combustion of the resulting dried product should be possible by adjusting the existing combustion apparatus used for solid fuel. The ignition temperature (T_i) at the DTG peak was about 177˚C, and DTG_{max} at a peak temperature (*i.e.*, the temperature at which the maximum weight reduction occurred) had the highest value, 0.0158%/s, for swine excreta fry-dried in refined oil.

5) Hg, Pb, Cd, As, and Cr were not detected in the dried excreta, but Al, which are included in the cohesive agent, were detected. Hg and As were not detected in the dried sewage sludge and Hg and Cd were not detected in the dried industrial sludge.

The present study indicates that swine excreta, sewage and industrial sludge dried by heating in B-C heavy oil and refined waste oil had features similar to those of bituminous coal. Thus, their combustibility is expected to be good when they are used as a waste-derived solid fuel. Additional further research is needed into topics such as the storage stability of the dried solid fuel, methods of handling malodorous gases, and water condensation treatment.

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