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Gasification of yeast industry treatment plant sludge using downdraft Gasifier

Azize Ayol, Ozgun Tezer and Alim Gurgen

ABSTRACT

Sludges produced in biological wastewater treatment plants have rich organic materials in their characteristics. Recent research studies have focused on the energy recovery from sludge due to its high organic content. The gasification process is a thermal conversion technology transforming the chemical energy contained in a solid fuel into thermal energy and electricity. The produced syngas as a mixture of CO, CH_4, H_2 and other gases can be used to generate electrical energy. The gasification of yeast industry sludge has been experimentally evaluated in a pilot scale downdraft-type gasifier as a route towards the energy recovery. The gasifier has 20 kg biomass/h fuel capacity. During gasification, the temperature achieved was more than 1,000 °C in the gasifier, and then the syngas was transferred to the gas engine to yield the electricity. A load was connected to the grid box and approximately 1 kWh electrical power generation for 1 kg dry sludge was determined. The characteristics of residuals – ash, glassy material – were also analyzed. It was found that most of the heavy metals were fixed in the glassy material. Experimental results showed that the yeast industry sludge was an appropriate material for gasification studies and remarkable energy recovery was obtained in terms of power production by using syngas.

Key words | energy recovery, gasification, syngas, yeast industry sludge

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INTRODUCTION

The gasification process, known as one of the advanced thermal conversion technologies, is capable of transforming the chemical energy contained in a solid fuel (like biomass) into thermal energy and electricity (Arena & Mastellone 2005; Bruno 2006). The most important by-product of this process is the synthesis gas called 'syngas', which is a mixture of CO, H_2, CH_4, and other gases that can be evaluated as fuel. This technology might be considered to play an important role in the future global energy infrastructure. As a solid fuel, biomass has been used for not only the generation of power and heat, but also the production of fuels and chemicals via gasification technology. The gasification process takes place at close to atmospheric pressure and temperatures from 700 °C to 1,000 °C (de Andres *et al.* 2011). The process has two distinct zones: oxidation and reduction. The oxidation zone generate gaseous products such as tar, H_2O, CO, CO_2, H_2, CH_4, C_mH_n, and char. In the reduction zone, often known as gasification zone, the char is converted into gas by the reaction with the gases from the upper zones (XIE *et al.* 2010).

Sludge produced during the wastewater treatment processes in domestic/municipal/industrial wastewater treatment plants (WWTPs) has been considered as a waste to be disposed of by using environmentally and economically appropriate methods. However, it is a resource that can be evaluated for generating of renewable energy. Therefore, thermal processing of the biological sludges produced at WWTPs can be promoted as a cost-effective and environmentally sound alternative in sludge management field. The sludge has a fuel merit, with its high calorific value, for energy recovery with the different valorization processes including gasification technology. From the point of view of their rich organic contents, the processed sludges by using auxiliary sludge treatment processes like thickening, stabilization, and dewatering units have been taken into account as biomass. The thermal processing of sludge has many advantages including the reduction of volume and weight, destruction of toxic organic compounds, and recovery of energy, but the economics should be carefully evaluated (Samolada & Zabaniotou 2014).

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The most critical variable in the gasification process is known as the fuel type. A wide range of fuel types exist from coal to wood to agricultural by-products. Each fuel type has a different shape, size, chemical composition, moisture content, and ash content. These properties affect how the fuel physically moves through the gasifier as well as its ability to be gasified (Purdon 2010). In this study, as a part of a large scale research project, the energy recovery from sludge, taken from an industrial yeast production WWTP, via the gasification process was investigated. The inspiration for the study is based on the successful gasification applications by using different organic materials like coal, walnut, and wood chips. The main objective of the study was to determine the gasification potential of the yeast industry sludge due to its rich organic content.

MATERIALS AND METHODS

Sludge sampling and characterization

Sludge cake samples were taken from a yeast industry WWTP located in Izmir, Turkey. The sludge cake having 18% of dried solids content (DS) was shaped in pelletized form and dried at 40 °C up to 90% DS for the further gasification process to be applied. Sludge characterization studies were first completed and then the sludge gasification studies were applied.

In the characterization studies, pH, salinity, electrical conductivity (EC), heavy metals (Ba, Cd, Cr, Ni, Pb, Zn, Cu, Mo, As, Sb, Se, Hg), DS, volatile solid content (VS), loss on ignition, low heating value (LHV), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), Fourier transform infrared spectroscopy (FTIR) and X-ray powder diffraction (XRD), proximate and ultimate (elemental) analyses, scanning electron microscopy – energy-dispersive X-ray spectroscopy (SEM-EDS), thermal gravimetric analysis (TGA), and differential scanning calorimetry (DSC) analyses were done. Most of the analyses were done according to *Standard Methods* (APHA 2005). Where there was a lack of any standard methodology, the most accepted protocols in the scientific studies were used. Some of the analytical devices and equipment used in the experimental studies are given in Table 1.

Gasification reactor used in the experimental studies and its operation

A pilot scale gasification reactor (downdraft type) including various levels of part count and welded state (downdraft reactor, gas cowling, hopper, cyclone, filter, vac/blower, burner, plumbing, instrumentation including temperature and VAC instrumentation, combined cyclone and packed bed filter for gas cleaning, stainless steel air preheating tubes, air preheating/syngas cooling stainless steel heat exchanger, etc.) was used for the sludge gasification studies. The reactor was supplied from All Power Labs (Berkeley, CA, USA) and mounted in the Treatment Plant Sludge Laboratory at the Department of Environmental Engineering in Dokuz Eylul University, Izmir. The reactor operation conditions were first tested and shown to be fully set up for sludge gasification studies. A photograph of the Power

Table 1 | Analytical devices used in experimental studies

Parameter	Standard method	Analyzer
TN	TS 8337 ISO 11261	VELP Scientifica DK series
TP	TS EN 13346	Perkin Elmer Lambda 25UV/Vis spectrometer
TOC	TS 12089 EN 13137	Hach Lange IL 550 – solid module
Sample preparation for heavy metals	EPA 3051, EPA3052	Berghof microwave (Speedwave MWS-3)
Heavy metals	SM 3120 B	ICP-OES/Perkin Elmer OPTIMA 7000 DV
Heating value	TS 2678, TS 2390	IKA C200 adiabatic calorimeter
TGA	ASTM TGA methods	Perkin Elmer TGA 4000
DSC	Perkin Elmer – Diamond DSC	
Proximate analysis	ASTM D3173, D3174, D3175	
Ultimate analysis	Leco Truspec CHN-S Analyzer	
FTIR	Perkin Elmer, Spectrum BX	
XRD	Rigaku – Rint 2200/PC (Ultima 3)	

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Pallet gasification reactor system which has 20 kg biomass fuel capacity per hour is shown in Figure 1.

Dried and pelletized yeast industry sludge with 2–4 cm sizes was filled into the hopper. Twenty kilograms of yeast sludge was supplied into the reactor every hour, amounting to 80 kg of dried sludge in total amount. Following the reactor feeding, a leaking test was carried out by setting gas blowers and air blowers and then the required pressure values were monitored. A propane torch was used to ignite the reactor system. After the reactor had reached sufficient temperature (at least 700 °C), when enough quality syngas was obtained, by closing the valve to the flare and using syngas, the engine valve was opened to transfer the syngas to the engine for producing electricity.

After the gasification study was completed with the sludge, the residuals – ash and glassy (vitrified) material – were sampled for further analysis to determine their characteristics. For this purpose, heavy metals (Ba, Cd, Cr, Ni, Pb, Zn, Cu, Mo, As, Sb, Se, Hg), DS, VS, and TOC were analyzed, and FTIR and SEM-EDS were undertaken. In the ash residue, TGA, TN and TP parameters were also determined. An eluate sample was prepared from glassy material by using elutriation procedure defined as in TS EN 12457-4 (2004) standard for leach testing. The heavy metals were also analyzed in this eluate sample.



Figure 1 | Downdraft-type Power Pallet gasifier.

RESULTS AND DISCUSSION

Dried sludge characterization

DS and VS results of the dried sludge were found as 95.10 ± 0.19% and 56.88 ± 0.10%, respectively. TOC value of the sample was 417 g DS/kg, which was compatible with VS analysis results. The pH of the dried sludge was neutral. EC and salinity values were analyzed as 2.12 ± 0.12 mS/cm and 0.07%, respectively. TN and TP were found as 4.52% and 1.33%. Heavy metal results of the sludge are given in Table 2. Regarding the heavy metal analysis, Ba, Cr, Cu, Ni, Pb and, Zn were higher than the other metals in the sample.

To evaluate the thermal properties of the sludge, proximate and ultimate analyses were done. The analysis results are summarized in Table 3. Oxygen value was calculated by using ultimate analysis results. LHV was found as 15.47 MJ/kg DS (3,700 kcal/kg DS). LHV of a material is proportional to C and H while it is inversely proportional to N and S.

TGA is used to characterize moisture and volatile contents of coal, biomass and other materials including treatment plant sludge (Jain *et al.* 2016). Further understanding about the combustion behaviors via TGA, the kinetics and the interaction between the sludge pellet properties and combustion parameters is considered as paramount importance for sludge–biomass pellets due to the potential high utilization value (Jiang *et al.* 2016). The thermogram of the dried sludge sample is shown in Figure 2. The derivative thermal gravimetry (DTG) curve was obtained by derivatization of the TG curve showing the mass loss to temperature or mass loss to time in thermogram. The dried sample exhibited three different regions having distinct mass loss. The first region represented the moisture loss region until approximately 200 °C. The second region, which was between end of the first region and until approximately 600 °C, represented the transition phase in which the organics in the sludge passed to the gas phase, and the third

Table 2 | Heavy metal results of dried sludge sample as mg/kg

Ba	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Hg	Se	As	Sb
153.49	0.25	181.44	74.59	5.22	70.08	14.86	135.97	0.10	1.89	0.77	0.06

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Table 3 | Proximate and ultimate results of dried sludge sample as mg/kg

Proximate analysis, % by weight on dry basis

Moisture	Volatile solids	Fixed carbon	Ash
4.90 ± 0.19	56.88 ± 0.10	29.60 ± 0.54	13.52 ± 0.44

Ultimate (elemental) analysis, % by weight on dry basis

Carbon, C	Hydrogen, H	Nitrogen, N	Sulphur, S	Oxygen, O
40.27	5.51	10.41	1.18	42.63

region, representing burning of fixed carbon, is between end of the second region and 700–800 °C. These areas were determined by calculations on the thermogram. Loss of volatile organic materials occurs rapidly after the first region; after reaching the peak it was gradually slowed down. Loss of the dried sludge in the second region was determined as 49.70% at 545 °C. The maximum combustion rate of volatile matters was found in between 200 and 500 °C, which was obtained at approximately 300 °C.

DSC analysis was also done by using a Perkin Elmer Diamond differential scanning calorimeter to observe the structural changes as a function of temperature under the heat flow, as depicted in Figure 3. The peaks in the derivative heat flow curve shows the changes in the sludge material (phase change, transition or combustion). A wide-range thermal change was obtained between 50 °C and 150 °C. The peaks observed in the temperature range between 91 °C and 212 °C showed that the sludge included different materials having different thermal properties. In addition to this, certain thermal changes were obtained in 225, 238, 252, 264, 275 and 295 °C.

FTIR peaks plotted in Figure 4 showed O-H and NH groups at 3,400–3,200 cm^{-1} while the hydrophobic character of the organic phase in the sample showed the methyl and methylene aliphatic groups COO-H, C-H, Csp_3-H at 3,200–2,800 cm^{-1}. FTIR peaks in the range of 1,400–1,800 cm^{-1} represented carboxylic acid, ketones, aldehydes, phenyl and fluoride (C = N, C = C, phenyl, C-O, F). The peak at 1,000 cm^{-1} represents the C-O bond (carbohydrates) and the peaks obtained in the range of 800–650 cm^{-1} identified C-N and C-X bonds in the sludge's structure.

XRD analysis is the recognition of chemical species of a sample. Atoms differ in size and in scattering in powder. Structurally, similar minerals of different chemical composition are determined with XRD analysis (Braxoley 2001). The sample was analyzed at 1,546

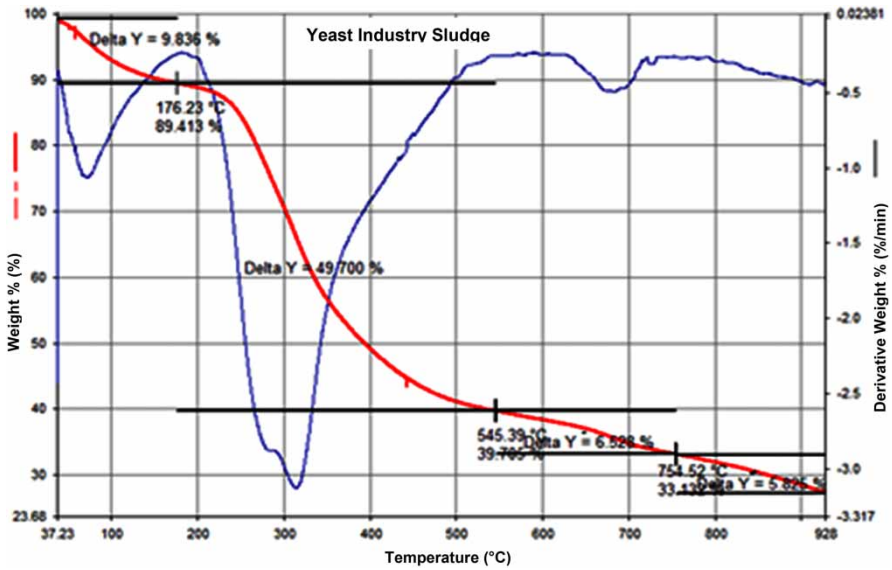


Figure 2 | Thermogram of dried sludge sample (temperature rate, 10 °C/min).

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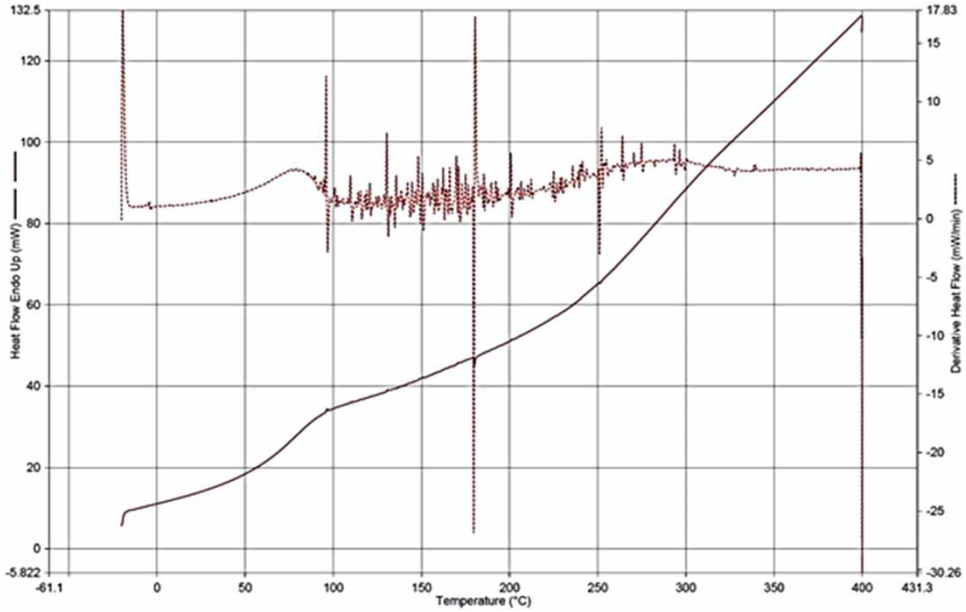


Figure 3 | DSC thermogram of dried sludge sample (temperature rate, 10 °C/min).

wavelengths and qualitative phase separation was carried out. According to the XRD results shown in Figure 5, the peak was assumed to be the same phase. According to this, the inorganic part of the sample mostly consisted of calcite ($CaCO_3$) and a certain amount of quartz (SiO_2).

SEM-EDS analysis results of the dried sludge are given in Figure 6. The sludge mainly contained C, O, Al, Si, S, Ca, and, in addition to them, the slightly available elements were N, P, Na, Mg, Fe, Cl, and K. The EDS results are also summarized in Table 4. Heavy metals, TOC, TN, and TP results were consistent with the SEM-EDS analysis.

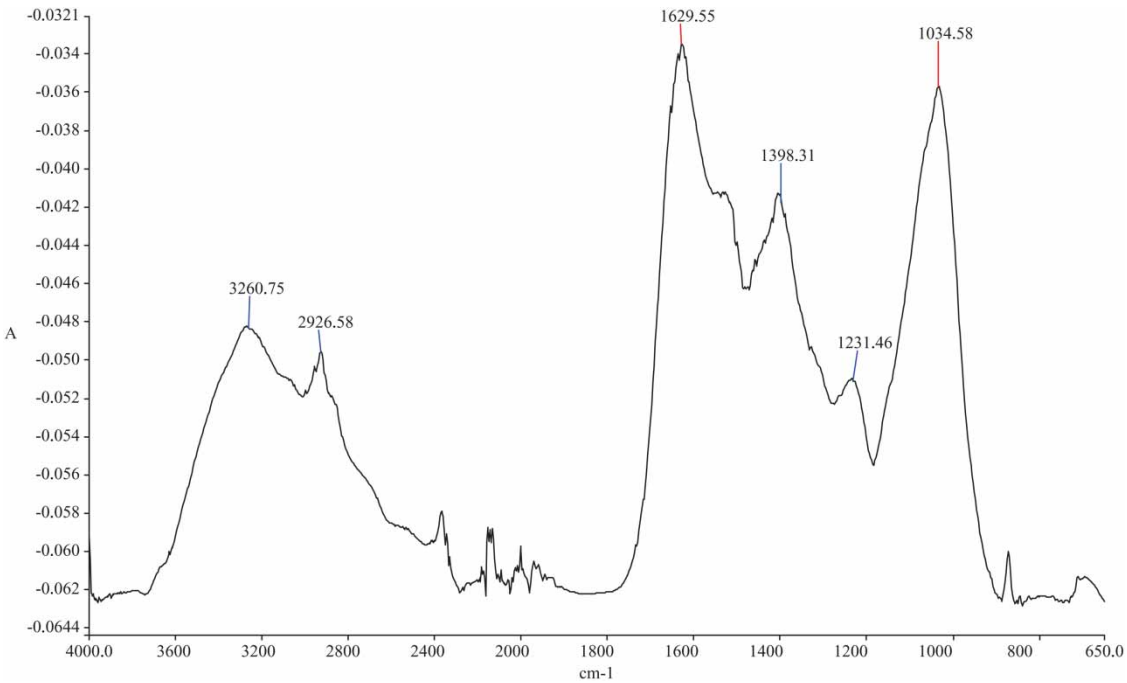


Figure 4 | FTIR results of dried sludge sample.

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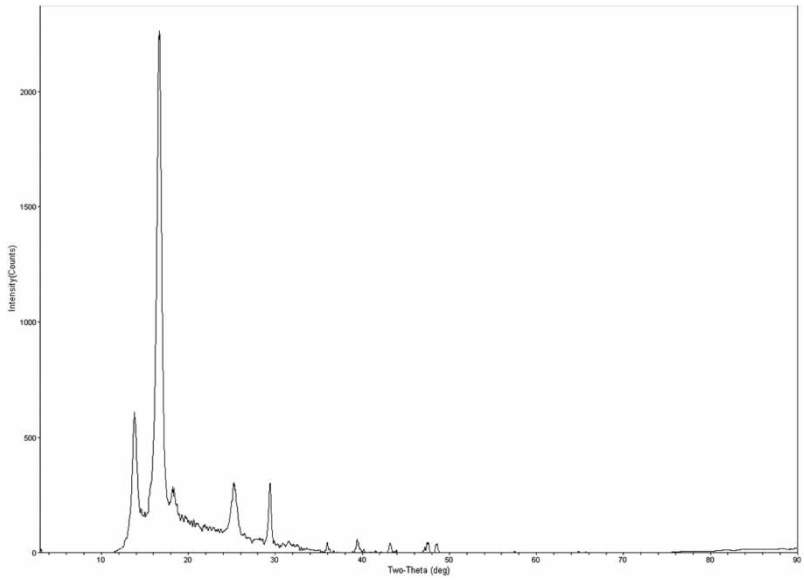


Figure 5 | XRD results of dried sludge sample.

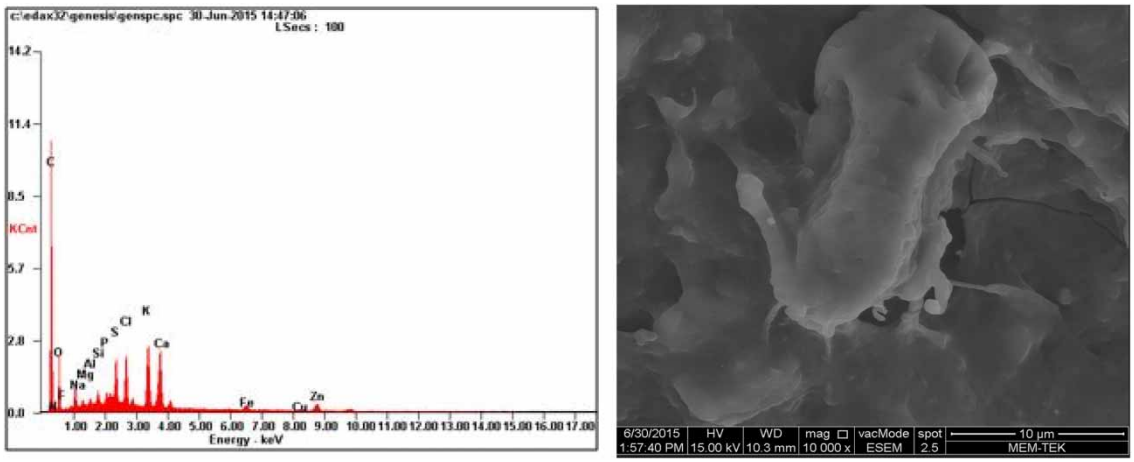


Figure 6 | SEM-EDS results of dried sludge sample.

Table 4 | EDS results of dried sludge sample

Element	Wt %	At %	Element	Wt %	At %
C	42.42	52.94	Si	0.69	0.37
N	7.69	8.23	P	2.68	1.30
O	33.70	31.58	S	1.57	0.73
F	0.39	0.30	Cl	0.37	0.16
Na	1.50	0.98	K	0.98	0.38
Mg	0.46	0.28	Ca	5.79	2.16
Al	0.40	0.22	Fe	1.37	0.37

Gasification studies of dried sludge

Following sludge characterization studies, dried yeast sludge in specified sizes, weighing about 80 kg, was added to the hopper of the gasifier reactor. After applying the leaking test and reaching the required pressure values, the gasification of the sludge material was monitored from the panel of the reactor. After the reactor had reached sufficient temperature (at least 700 °C), when enough quality syngas was obtained, by closing the valve

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to the flare and using syngas, the engine valve was opened to transfer the syngas to the engine for producing electricity. However, during this exothermic reaction, the temperature achieved was more than 1,000 °C in the gasifier. Depending on this temperature, the produced high quality syngas was transferred to the gas engine to yield the electricity. During this work, a load was connected to the grid box and approximately 1 kWh electrical power was generated for 1 kg yeast sludge used. The produced syngas composition was not constantly measured to protect the pilot scale reactor from a possible gas leaking. However, it was analyzed once by using a Draeger X AM 7000 device. The gas composition was found to be around 20% CO, 10% CO_2, and 5% CH_4 by volume. Ptasinski *et al.* (2006) have reported that the syngas composition produced from untreated wood was 17.7% CO, 12.6% CO_2, 22.7% H_2, 1.3% CH_4, and 38% N_2.

Table 5 | Emission values at the startup phase of the gasification study

Measurement	Unit	1	2	3	4
Gas temp.	°C	628	649.4	509.5	638.6
O_2	%	6.7	6.1	10	6.3
CO	ppm	312	231	306	372
	mg/m^3	389	288	382	464
	$mg/3\%O_2$	490	348	627	568
SO_2	ppm	134	122	54	75
	mg/m^3	383	348	154	214
	$mg/3\%O_2$	482	420	252	262
NO_x	ppm	674	517	774	907
	mg/m^3	926	710	1,064	1,247
	$mg/3\%O_2$	1,167	858	1,747	1,528
NO_2	mg/m^3	1,383	1,061	1,589	1,862
	$mg/3\%O_2$	1,743	1,283	2,609	2,282
CO_2	%	8	8.3	6.1	8.2
LOSS	%	34.7	34.7	35.4	34.5
EFF	%	65.3	65.3	64.6	65.5
Exhausted air		1.46	1.40	1.91	1.42

While the syngas was being exhausted from the flare at the startup phase of the gasification study, emission measurements shown in Table 5 were done. Emission limits for a half-hour (Official Gazette 27721, 06.10.2010, which is consistent with the EU Waste Directive) in the Turkish regulation gives the SO_2 limit as 50–200 mg/m^3, NOx-NO_2 limit as 200–400 mg/m^3, and CO limit as 150 mg/m^3. At the beginning of the gasification, the emission results were considered as tolerable pollution because the combustion zone of the reactor had normal gasifying temperature. After the startup phase, depending on the consumed O_2, CO was reduced.

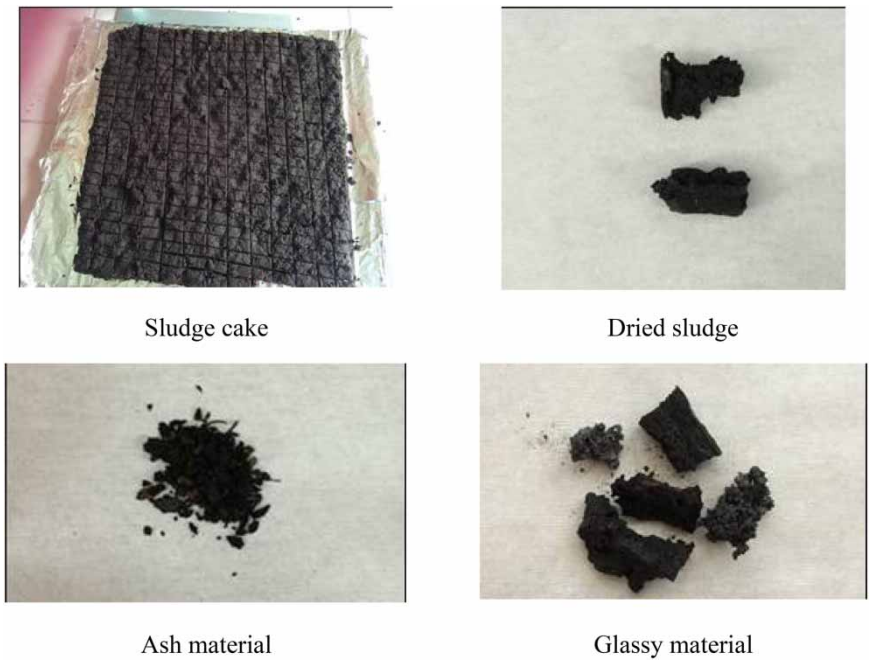


Figure 7 | Photographs of the ash and glassy material after gasified of the yeast sludge.

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Table 6 | Heavy metal results of ash sample as mg/kg

Ba	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Hg	Se	As	Sb
315.84	1.72	446.32	272.972	6.07	335.72	55.55	909.72	–	0.69	4.40	0.24

Properties of residual materials – ash and glassy material – occurring in gasification studies

Following the gasification studies, experiments were done to determine the characteristics of the residual materials. Some photographs of sludge cake, dried sludge, and the material samples are given in Figure 7.

DS and VS values of the ash material were determined as $94.08 \pm 1.69\%$ and $34.49 \pm 2.11\%$, respectively. While the pH value of the dried sludge was neutral, it was very alkaline in the ash sample ($pH = 10.2$). EC and salinity values were analyzed as 5.2 mS/cm and 0.07%, respectively. TN and TP were found as 0.49% and 1.06%. Heavy metal results of the ash material sampled are summarized in Table 6. The heavy metal results showed that Ba, Cr, Cu, Ni, Pb and Zn were higher than the other metals, as in the original sample. However, the results were higher than those in the original sample. It might be that the most of the metals were concentrated in the ash sample.

The ultimate analysis results of the ash sample are given in Table 7. Oxygen value was calculated by using ultimate analysis results. The values except for C were lower than those in the dried sludge sample. The TG/DTG thermogram of the ash material is depicted in Figure 8. The material exhibited two different regions having distinct mass loss. The first region represented the moisture loss region until approximately 200 °C as in the dried sludge sample. The second region was beyond approximately 600 °C, represented as burning of fixed carbon. The loss of ash material in the second region was determined as 12%.

Regarding the FTIR and XRD results of the ash sample, not shown here, FTIR peaks were obtained similar to those in the dried sludge sample while XRD analysis showed that the ash sample mainly consisted of calcite. SEM images for ash material and glassy material are given in Figure 9. The SEM-EDS analysis results of the ash material indicated that the ash sample mainly contained C, O, Al, Si, S, and

Table 7 | Ultimate analysis results of ash sample as mg/kg

Ultimate (elemental) analysis, by weight on dry basis

Carbon, C	Hydrogen, H	Nitrogen, N	Sulphur, S	Oxygen, O
55.61	2.54	1.2	1.07	39.58

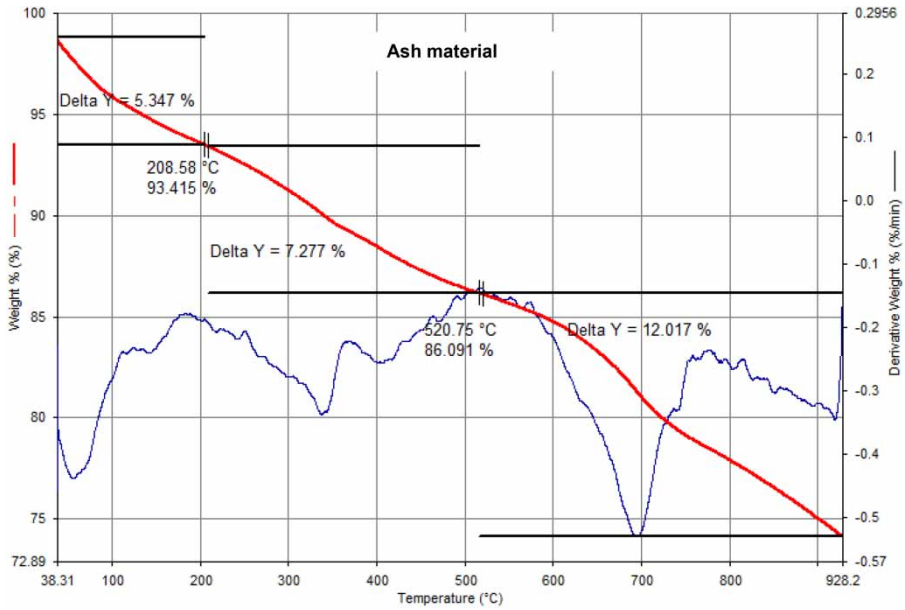


Figure 8 | Thermogram of ash sample (temperature rate, 10 °C/min).

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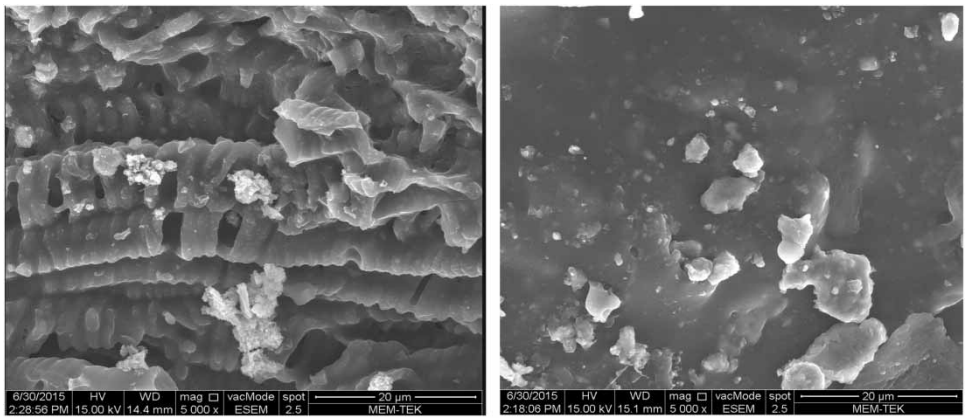


Figure 9 | SEM-EDS results of ash sample (left) and glassy sample (right).

Ca; in addition to them, the slightly available elements were N, P, Na, Mg, Fe, Cl, and K. The EDS results are summarized in Table 8. Heavy metals, TN, and TP results were consistent with SEM-EDS analysis. The ash material is valuable material derived from the gasification studies and could be evaluated as adsorbent material or soil conditioner. Spinosa *et al.* (2011) has reported that the material with rich nutrient elements including P, C, Fe and other micro-elements can be used in the soil after mixing with soil to improve the soil quality. They also stated that, when adding this to the soil at the appropriate amount, the soil conditioner has the capacity to absorb and release N, P and other nutrient elements, and also to keep water and release water slowly. However, heavy metal concentrations play an important role in the land application.

Table 8 | EDS results of ash sample

Element	Wt %	At %	Element	Wt %	At %
C	65.69	77.26	P	0.46	0.21
N	1.70	1.72	S	1.84	0.81
O	16.44	14.52	Cl	2.21	0.88
F	0.00	0.00	K	2.90	1.05
Na	1.89	1.16	Ca	3.15	1.11
Mg	0.48	0.28	Fe	0.57	0.14
Al	0.33	0.17	Cu	0.05	0.01
Si	0.62	0.31	Zn	1.67	0.36

DS and VS values of the glassy material were found as 98.23% and 0.03%, respectively. The pH value of the glassy material was neutral (pH = 7.4). EC value of the sample was determined as 6.58 mS/cm. Heavy metal results of the glassy material and eluate sample are given in Table 9. The heavy metal results showed that Ba, Cr, Cu, Ni, Pb and, Zn were higher than the other metals, as in the original sample. However, the results of the glassy material were higher than those in the original sample. It might be that the most of the metals were concentrated in the ash and glassy materials. Regarding the lower heavy metal concentrations in the eluate sample, it could be concluded that most of the heavy metals were fixed in the glassy material. Spinosa *et al.* (2011) have pointed out that the glassy material can have big porosity, high strength, and lightweight and heavy metal ions. The immobilization capacity is obtained after the process of melting, re-organization and expansion.

FTIR peaks not shown here were obtained as similar to those in the ash sample. According to XRD analysis, the glassy material mainly consisted of calcite and quartz. SEM-EDS analysis results showed that the sample mainly contained C, O, Al, Si, S, and Ca; in

Table 9 | Heavy metal results of glassy material sample and eluate sample

Material	Ba	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Hg	Se	As	Sb
Glassy material (mg/kg)	335.16	0.36	127.88	106.79	8.53	52.39	29.26	199.95	0.01	1.29	2.31	0.24
Eluate sample (µg/L)	38.86	3.69	97.67	204.50	30.33	119.2	25.85	379.4	–	2.90	12.93	1.21

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Table 10 | EDS results of glassy material

Element	Wt %	At %	Element	Wt %	At %
C	63.25	72.31	P	1.64	0.73
N	6.16	6.04	S	1.23	0.53
O	20.43	17.54	Cl	0.23	0.09
Na	0.63	0.37	K	0.58	0.20
Mg	0.33	0.18	Ca	3.71	1.27
Al	0.41	0.21	Fe	0.64	0.16
Si	0.75	0.36			

addition to them, the slightly available elements were N, P, Na, Mg, Fe, Cl, and K. The EDS results are summarized in Table 10. Heavy metal results were consistent with SEM-EDS analysis.

CONCLUSION

Gasification potential of yeast industry sludge was investigated in this study. A downdraft gasification reactor was used at pilot scale during the experimental studies. The concluding remarks from the research study could be given as follows.

- FTIR results showed that the main groups in the yeast industry sludge were aliphatic chains with double bonds, as well as carbonyl, hydroxyl and N–H groups in organic compounds.
- The results of TGA/DTG showed that the sludge has three regions; up to 200 °C, sludge moisture loss region; from 200 °C up to 500–600 °C, thermal decomposition of volatile matter in sludge; and last region from 600 °C up to 700–800 °C, thermal decomposition of fixed carbon (refractory predominate, such as N-alkyl long chain structures, and saturated aliphatic chains). However, the TGA/DTG showed that the ash sample has two distinct regions.
- Highest combustion rate for the sludge was found around 300 °C. In the gasifier, temperature higher than 1,000 °C was achieved.
- Approximately, 1 kWh electrical power was generated for 1 kg yeast sludge used.
- Regarding the ash sample, it can be said that the material has high TP values. It could be used a soil conditioner and/or adsorbent material regarding the other components.
- Experimental studies showed that the yeast industry sludge having rich organic content could be used for energy recovery purpose via gasification.

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