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RESEARCH ARTICLE

Co-combustion of distillery sludge and coal for application in boiler and subsequent utilization of the generated bottom ash

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Abstract

Combustion stands as one of the essential methods in resource recovery for disposal of distillery sludge. In this study, sludge along with coal has been considered an option for co-combustion in the grate furnace aiming for further application as a boiler fuel. Detailed analysis was carried out to verify the feasibility of co-combustion of sludge with coal. Distillery sludge was blended with coal as a mixed fuel at co-combustion ratios of 20%, 30%, and 40% in grate furnace. The results of the analysis indicated that the combustion with 40% sludge mixed coal is suitable for application as a fuel in boiler. According to the chemical composition of bottom ash, weight loss from 460 to 800°C indicated the presence of C–C and C–H. Also, EDX and XRD analyses of mixed fuel was carried out to determine the mineralogical composition. The presence of quartz (SiO_2), mullite ($3Al_2O_32SiO_2$), and hematite (Fe_2O_3) present in the ash can be used as mineral additives in cement industries. The study also provided a promising approach towards diverting combustion bottom ash from landfills for its utilization in various industries which can be a possible cost-effective solution.

Keyword Combustion · Grate furnace · Distillery sludge · Coal · Boiler

Introduction

Distilleries are important sub-units of sugar production industries, and a huge quantity of effluent is generated in the lagoon during the processing of molasses in distillery industries where the solid particles settle in the lagoon to form sludge (Khardenavis et al. 2008). This distillery sludge contains a high concentration of metals, nutrient with inherent energy potential, which can probably be recovered by various wastes to energy processes like anaerobic digestion, thermal conversion, etc. However, thermal conversion (combustion) has an advantage over anaerobic digestion in terms of volume reduction, toxic substance decomposition, and recovery of embedded energy (Hao et al. 2020).

The combustion of the biomass like sludge can be achieved on a commercial scale by adopting suspension burners, fluidized and fixed bed combustion systems, etc. (Kijo-Kleczkowska et al. 2016). Grate furnace is very useful for the combustion of biomass-based fuels with varying particle size and higher moisture content and ash content. Grate furnace is specifically designed for the homogeneous distribution of fuel (Koziol and Koziol 2019; Zhang et al. 2017). Various types of grate furnaces viz. rotating grates, fixed grates, travelling grates, vibrating grates, and moving grates are available (Van Kuijk et al. 2008).

Combustion of sewage sludge is mostly practiced, but this treatment facility lacks practice in the case of distillery sludge (Soria-Verdugo et al. 2020). Due to the low heating value and volatile contents, distillery sludge cannot be self-sustainably combusted. Therefore, co-combustion of sludge with various other biomasses like municipal solid waste (MSW), wood, or

Highlights

- *Study outlined an approach towards utilization of distillery sludge.*
- *Carbon content of the substrate ranged from 40.53 ± 0.05 to 32.68 ± 0.12%.*
- *Sludge mixed with coal was co-combusted in furnace to check the boiler applicability.*
- *Bottom ash contained quartz (0.03–0.44%), mullite (0.05–0.18%), and hematite (0.30–0.77%).*
- *Ash containing SiO_2+Al_2O_3 is necessary for industrial application.*

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supplementary as a coal was found to be beneficial for the energy generation. The heat energy generated from the waste biomass was also found to be the efficient conventional process and also successful for the application on the larger scales (Pio et al. 2020). Therefore, it is possible to recover the heat energy in the form of a combusted product from sludge (Oladejo et al. 2019).

Nevertheless, the dilution effect of co-combustion of sludge with other fuels to produce sludge ash, which has further usage in various industries, is also under practice (Zhang et al. 2020). The sludge combustion for energy recovery yields a significant amount of bottom ash as a combustion residue (Chen et al. 2020), and comprehensive research has been performed to identify its potential application (Wang et al. 2020). Bottom ash has similar mineralogical and physical properties which can be further used as a replacement for cement and aggregates in structural concrete, etc.(Argiz et al. 2018). However, sludge comprised various components like metalloids and heavy metals (Pb, Cr, As, Ni, Hg, and Cd) that can be accumulated in the ash (Tangahu et al. 2011). Ash collection methods are different for different combustors, and the transformation and distribution of elements into the ash fully differ with sample and depend on the type of combustor used (Kleinhans et al. 2018).

Researchers have also studied the co-combustion of sludge with coal and found it to be feasible from environmental, economic, and energy point of view (Lei et al. 2020). The study on distillery sludge combustion is not covered yet and hence thermal treatment is reflected in mind to produce the bottom ash which is approved by regulations. The existing bottom ash cannot fulfill the current industrial demand and so blending with natural aggregate product, that provides economic and environmental benefits of ash recycling as a consistent and sustainable aggregate source, may be carried out (even at low proportions of distillery sludge bottom ash) (Schafer et al. 2019).

In recent years, the major concern has been the use of alternative renewable energy sources in replacement of coal. However, quite limited researches have been carried out on the utilization of distillery sludge as an energy source. To bridge this gap, the study aimed to check the combustion behavior of distillery sludge-mixed coal in a grate furnace and check its applicability as the boiler fuel. The bottom ash generated during the experiment was analyzed for the structural, mineralogical, and thermogravimetric properties for its reuse and its utilization as construction industrial purposes. Novelty of the study is that it provides alternate solution as distillery sludge along with coal to be used in the existing boiler as combustion fuel with proper modification. It also provides other suitable alternative to the cement and construction industry and minimizes the environmental implications due to the direct disposal of distillery sludge.

Materials and methods

Sample collection and preparation

Coal samples were collected from the boiler section of the distillery industry, and the sludge samples were collected in double-lined polythene bags from the rehabilitated lagoon of the distillery industry. Approximately 75–80 wt.% of coal particles used in the study had a size in the range up to 7 mm, while the rest 20–25 wt.% of them have particle size of 200 mesh (0.074 mm). The sludge sample was blended with coal to generate a different proportion of mixed sludge coal designated as G1, G2, and G3. The ratio of sludge/coal mixture was 20/80, 30/70, and 40/60 (% wt./wt.) for G1, G2, and G3 mixtures, respectively (Sever Akdag et al. 2018; Dhote et al. 2020). Coal-mixed sludge in the ratio 50:50 could not be taken for the study as there was a difficulty in their homogeneous mixing.

Sample analysis

Proximate, ultimate, and burnout efficiencies

The sludge mixed with coal was studied by using standard methods (Bureau of Indian Standards (BIS)-IS 10158-1982) for parameters like moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (AC). The ultimate analysis was performed by adopting the Indian Standard (IS) procedures for a test of coal and coke (IS: 1350-Part-IV/Section-I-1974). The ultimate analysis included carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) (Fu et al. 2019). All the experiments were carried out thrice to minimize the error during performance, and mean ± standard error of 3 experiments was analyzed. Burnout efficiency (BE) was calculated for the chemical analyses of the coal and ash as per Eq. (1) (Vershinina et al. 2019).

$$\mathrm{BE\%} = \Bigl[1-\mathrm{Ao}(100-\mathrm{Ac}) \div \Bigl(\mathrm{Ac} \times (100-\mathrm{Ao})\Bigr] \times 100 \qquad (1)$$

where Ao is the ash percentage of coal and Ac is the ash percentage of bottom ash.

All the parameters were taken on a dry basis.

Equation (1) is based on the assumption of consistency of ash content in the parent coal and bottom ash (% by wt.).

Design of experiment

Grate furnace system for combustion study

The schematics of the fixed grate furnace system used in the present combustion study are depicted in Fig. 1**.**

The grate furnace used in the present study consists of a fixed grate in two stages having a diameter of 10 and 30 cm,

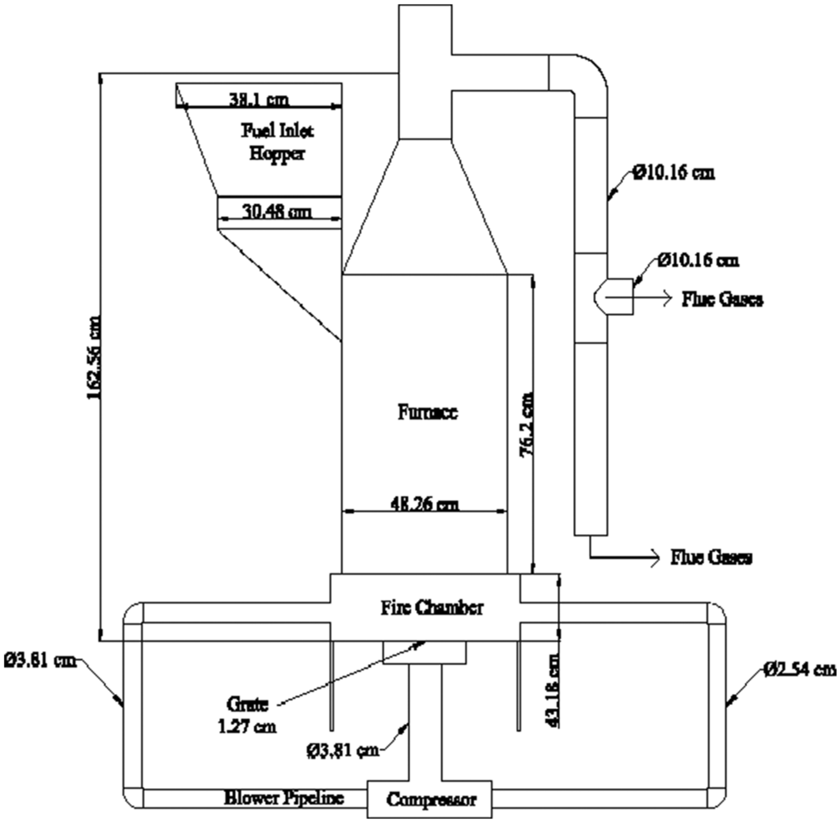

Fig. 1 Schematics of the pilot-scale grate furnace system for the combustion of coal mixed sludge

respectively. The second grate is mounted over the first grate with a gap of 5 cm which is a steel-based sieve as depicted in Fig. 1. The mixed sludge coal is dropped through a hopper attached with the furnace. Further, the grate and fire chamber have appropriate water sealing arrangement as indicated in the schematics (Fig. 1). Water seal in the furnace prevents the escape of hot flue gases and directs it to the furnace. The grate furnace is made up of cast iron with an internal ceramic lining of 25 mm and other details of grate furnace with dimensions as given in Table S1. The grate furnace is attached with a hopper having a water seal arrangement for the feed of the sludge-mixed coal. The dimension of the hopper is 10 cm × 10 cm. The air is supplied through a hosepipe attached with a compressor having 1 hp motor with a blowing capacity of 440 l/min. The airflow to the furnace is controlled by throttling the air supply pipeline through a valve arrangement to maintain a flow of 150–200 l/min. The top of the furnace is connected with a pipe having a diameter of 10 cm as a sampling port as shown in Fig 1.

Combustion study in grate furnace

The combustion of coal and coal-mixed sludge was carried out in duplicate in 7 days. Thus, all the observations presented in the study are the average of two sets of experiments. The coal-mixed sludge was fed at a rate of 10 kg per batch with an interval of 10 min. The fire chamber was heated with the insertion of fired jute cloth soaked in diesel whenever there was no electricity supply to the grate furnace. Most of the time grate furnace was heated through the supply of electricity using the control panel. The temperature of the fire chamber was always maintained in the range 950 to 1000°C. At the initial stage of combustion of coal-mixed sludge, the flue gases emerge and pass through the furnace chamber and are finally discharged through the vent pipe, as shown in Fig. 1. The flue gas samples were collected when the discharge of the flue gas achieved a pseudo steady state. The combustion reaction in the grate furnace started as when the coal-mixed sludge was fed into it. The total feeding time of the coal-mixed sludge for 10 kg of feed/batch lasted for 40 min at a feed rate of 2.5 kg/10 min. The pseudo steady state of the combustion was achieved within 60 min. (Based on the discharge flow rate of the flue gases and temperature of the furnace). After complete combustion of the coal-mixed sludge, it was subjected to cool. After 5 h of the cooling, the bottom ash sample was collected for purposes of analysis (Da Costa et al. 2018; Yin and Li 2017).

The coal and sludge mixed with coal samples as C, G1, G2, and G3 were combusted in a pilot-scale grate furnace system. The prepared coal-mixed sludge samples in different proportions were sun-dried and fed through the hopper at a rate of 2.5 kg/10 min with a total feed of 10 kg/batch. Air was supplied into the combustion reactor in the range of 180–200 l/min.

Methods for analysis of bottom ash

The bottom ash produced during the combustion of samples C, G1, G2, and G3 in grate furnace was collected and analyzed. The bottom ash samples were firstly dried in a hot air oven at 110°C for 24 h to remove the moisture. The samples were crushed in a crusher and crushed bottom ash was then passed through 250 μm standard sieve to prepare the grounded bottom ash.

X-ray diffraction (XRD) technique was used to identify the mineral phases present in bottom ash sample by using “Philips X pert diffractometer (Model: PW 1710)” and detector used in the instrument scanned at the scattering angle of 2 . The analysis was carried out at room temperature to identify the crystalline phases, and the results obtained with respective peaks were identified by peak position and intensities (Osholana et al. 2020). In scanning electron microscope (SEM) analysis, the sample was coated with gold nanoparticles by using an initial agar manual sputter (Murtey and Ramasamy 2016). “Energy dispersive x-ray spectroscope (SEM-EDX)” (Model: TESCAN make) was used to determine chemical composition, morphology, and loss on ignition (LOI) of bottom ash sample. In the SEM-EDX analysis, energy emitted was different for element to element with overlapping of a small peak. During the surface scanning or mapping operation, eight X-ray emission lines were scattered on the surface of the sample. Resolution for the scanning of the material was taken about 10 μm in depth. SEM spectrograph was determined in the magnification of ×1000 (Predeanu et al. 2016).

Thermogravimetric analysis and heavy metals analysis

Thermal stability up to 1200°C and material composition of substrate combination was analyzed in thermogravimetric analysis (TGA) (STA, 6000, PerkinElmer, Germany) comprising simultaneous thermal analyzer to calculate the LOI (%). To show weight gain/loss due to the dehydration, decomposition and oxidation were done through the TGA analysis (Li et al. 2019). It depends on the physico-chemical properties, chemical compounds, mineral composition, solid surface area, etc. (Ghosh and Goel 2014). The toxicity characteristic leaching procedure (TCLP) was used for leaching of the sample. The crushed ash sample with a size less than 200 μm was dried at 120°C for 12 h and cooled. The “inductively coupled plasma optical emission spectroscopy (ICP-OES)” was used to evaluate heavy metals by following standard procedure. The determination of the presence of heavy metals like “arsenic (As), aluminum (Al), barium (Ba), calcium (Ca), iron (Fe), copper (Cu), lithium (Li), lead (Pb), magnesium (Mg), zinc (Zn), selenium (Sr), and manganese (Mn).” Analysis has done using ICP-OES (iCAP 6300DUO SERIES, Thermo Fisher, USA).

Results and discussion

Characteristics of sample fed to the grate furnace

Proximate and ultimate characteristics and burnout efficiency

Proximate characteristics of C, G1, G2, and G3 fed to the grate furnace before combustion were analyzed for MC, AC, FC, and VM, and the results are provided in Table 1. The characterization of the sludge is available in a previous study carried out by Dhote et al. (2020). The AC of coal-mixed sludge samples increased from 30.7 ± 0.19 to 34.47 ± 0.15% with an increase in the proportions of sludge. Similarly, the VM content of coal-mixed sludge samples increased from 28 ± 0.07 to 32.35 ± 0.07%. The FC of the coal-mixed sludge samples decreased from 34.13 ± 0.09 to 24.68 ± 0.06% with increase in sludge proportion.

The coal-mixed sludge samples fed to the grate furnace under the present investigation were analyzed for elemental composition, and the results are presented in Table 1. The elemental analysis of the samples G1, G2, and G3 indicated that the carbon content decreased from 40.53 ± 0.05 to 32.68 ± 0.12% as the sludge proportions increased from 20 to 40% (wt./wt.). Thus, the addition of sludge to the coal showed a decrease in carbon content in the sample. Further, the sulfur content of samples increased 10-fold with an increase in sludge proportions with a reduction in coal amount as sludge contains a higher amount of sulfur compared to that of coal (Pires et al. 2020). The calorific value of the sludge-mixed coal sample decreased from 4220 ± 3.9 to 3350 ± 4.5. Sludge contains lower carbon value and combustion properties which is ultimately responsible for its lower calorific value. When the sludge was mixed with coal in different proportions, the calorific value was decreased affecting the combustion behavior in the furnace (Kim et al. 2017).

Based on the initial characterization of the substrate, a hypothesis was drawn that the sludge along with the coal can be used for combustion study. The aim is to generate bottom ash which can be further utilized in the various construction industries and can ultimately reduce the global sludge disposal problem. The prediction of research hypothesis is that the sludge mixed with coal at optimum ratio can be utilized in various industrial boilers. The carbon content, calorific value, and other fuel parameters of sludge-mixed coal samples are the independent variables. While combustion behavior and bottom ash composition act as dependent variables in the study.

A series of a chemical reaction was carried out during combustion of coal-mixed sludge sample. It is noteworthy to mention that the efficiency of combustion depends on temperature, time, and turbulence (TTT). The ratio between the locally

Table 1 Proximate and ultimate analyses and burnout efficiency of substrate

Sl. No.	Sample	MC (wt.%)	AC (wt.%)	VM (wt.%)	FC (wt.%)	N (wt.%)	C (wt.%)	H (wt.%)	S (wt.%)	BE (wt.%)	Calorific value (kcal/kg)
1.	C	5.45 ± 0.15	24.47 ± 0.21	25.12 ± 0.05	44.96 ± 0.10	0.68 ± 0.12	59.8 ± 0.05	3.93 ± 0.11	0.44 ± 0.09	98.28 ± 0.25	5298 ± 4.6
2.	G1	7.17 ± 0.18	30.7 ± 0.19	28 ± 0.07	34.13 ± 0.09	1.13 ± 0.09	40.53 ± 0.05	3.91 ± 0.09	0.39 ± 0.12	95.74 ± 0.33	4220 ± 3.9
3.	G2	7.76 ± 0.11	32.16 ± 0.17	30.1 ± 0.08	29.98 ± 0.08	1.27 ± 0.10	34.79 ± 0.05	3.69 ± 0.11	0.24 ± 0.13	93.14 ± 0.29	3846 ± 4.1
4.	G3	8.5 ± 0.19	34.47 ± 0.15	32.35 ± 0.07	24.68 ± 0.06	1.28 ± 0.09	32.68 ± 0.12	3.94 ± 0.13	0.36 ± 0.14	90.37 ± 0.22	3350 ± 4.5

MC, moisture content; *AC*, ash content; *VM*, volatile matters; *FC*: fixed carbon; *C*, carbon; *H*, hydrogen; *N*, nitrogen; *S*, sulfur

available and stoichiometric amount of air used for combustion is called excess air ratio (λ) which is the crucial combustion parameter. The successive homogeneous and heterogeneous reactions like drying, de-volatilization, char combustion, gasification, and gas-phase oxidation occurred during the combustion of coal-mixed biomass, and the time required for each response depends on the fuel properties, size, and TTT. For efficient burning, the λ is always maintained more than 1 (Kumar et al. 2018).

The burnout efficiency of coal and coal-mixed sludge samples are presented in Table 1. The burnout efficiency of coal-mixed sludge decreased from 95.74 to 90.37%. In comparison, burnt efficiency in coal (without sludge) was observed to be 98.28%. The decrease in burnout efficiency might be attributed to the composition of sludge, i.e., organic mixed with inorganic constituents. As the sludge proportion increases, the inorganic content might increase which might be partially affecting burnout efficiency of the coal-combined sludge sample. It has also been observed that the coal-mixed sludge samples even after drying have less moisture content, but it has a tendency to absorb the moisture from the atmosphere. The extent of increase in the moisture content is governed by the proportion of sludge present in the coal-mixed feed. The coal-mixed sludge samples with a higher proportion of sludge contain more moisture in the feed of the grate furnace, thereby decreasing the burnout efficiency of the samples (Vershinina et al. 2019).

According to Coal India Limited (CIL) for non-cooking coal, the approximate cost per ton is Rs.2423 (US$33.20) that depends on the basis of gross calorific value (GCV) and carbon content of the coal. If the coal is replaced with 20, 30, and 40% of readily available and no-cost distillery sludge, around Rs.484.6 (US$6.64), Rs.726.9 (US$9.96), and Rs.969.2 (US$13.28), respectively can be saved per ton of fuel used. The amount of coal replaced with sludge which is the waste product of distillery industry for the samples G1, G2, and G3 is 200, 300, and 400 kg, respectively.

The heat generated in the process was calculated by using Eq. (2) (Jouhara et al. 2018):

$$Q = mC\text{p}\Delta T \qquad (2)$$

where Q is the heat generation in the process (kJ), M is the mass of sample (kg), Cp is the specific heat of the sample $\left(\frac{\text{kJ}}{\text{kg}^\circ\text{C}}\right)$, and T is the initial and final temperature difference (°C).

During combustion of coal having 10 kg of sample with the specific heat of 0.33 kJ/kg °C with temperature rise from room temperature (37°C) to 1000°C (T = 963°C), the heat generated was observed as 3177.9 kJ, and during the combustion of G1, G2, and G3 with the calculated specific heat of 0.264, 0.231, and 0.198 kJ/kg °C, the heat generated in the process was found to be 2542.32, 2224.53, and 1906.74 kJ, respectively.

Characteristics of bottom ash

Evaluation of LOI using TGA

The unburnt carbon present in bottom ash produced during combustion followed by determination of end-use of bottom ash is evaluated by LOI test. Thermal decomposition peak at different temperature ranges and the primary weight loss at respective temperature are represented in the TGA curve, as shown in Fig. 2a. The first peak due to the loss of chemically and physically bounded water was observed at 30 to 100°C. The peak observed due to the mass loss at 460°C indicated the C–H bond dehydroxylation and between 600 and 800°C, the peak was due to decarbonization of C–C bond, which is an important property to use the ash in the cement industry (Zhou et al. 2020).

The TGA of bottom ash produced during the combustion of coal-mixed sludge in different proportions was carried out. The LOI of coal is 3.2%, while for the sample G3, LOI showed 3.9% as shown in Fig. 2b. In the sample G3, LOI due to the loss of moisture up to the temperature of 100°C is 0.534%. Above 100°C, the LOI is 3.66% and thus the overall LOI is 3.9%. The bottom ash was having a LOI of less than 5% which might be suitable for use in the cement industry subject to meeting the requirement in terms of mineralogical property. If LOI is less than 5%, it is confirmed to be F-type ash as per IS 3892-I (1997).

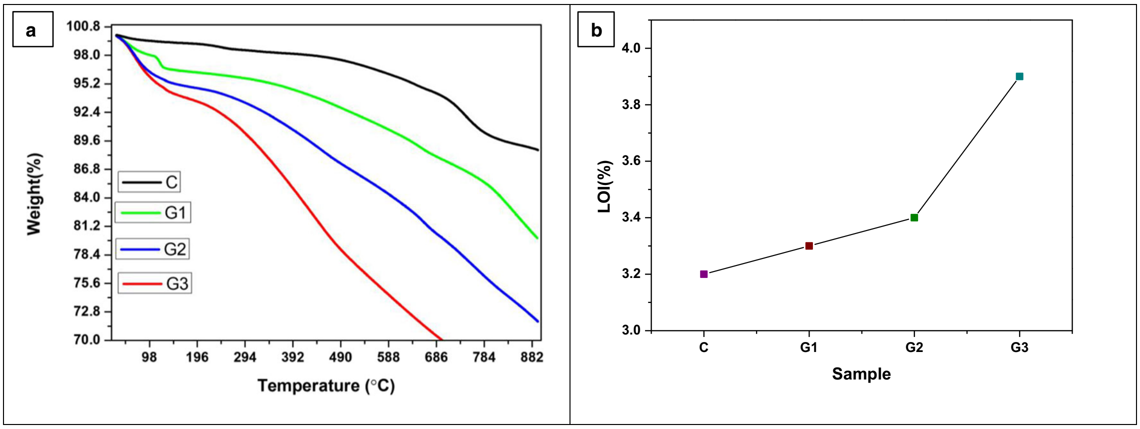

Fig. 2 TGA analysis of bottom ash. **a** Mass loss (%) by TGA; **b** LOI (%)

Evaluation of mineralogical composition using XRD and SEM-EDX techniques

The SEM of the bottom ash sample produced by the combustion of the coal and coal-mixed sludge in grate furnace is presented at ×1000 magnification, as shown in Fig. 3. The bottom ash has irregular, large size, rough surface texture, and dark grey color due to unburnt carbon and carbon-mixed sludge (Zabielska-adamska 2020). The figures represented that some of the finer particles, such as cenosphere stick to the coarse particles which help the structural material as a sound-absorbing material and can also be used as aggregate to develop lightweight concrete (Kim and Lee 2011). EDX graph of bottom ash with coal and coal-mixed sludge is shown in Fig. 4.

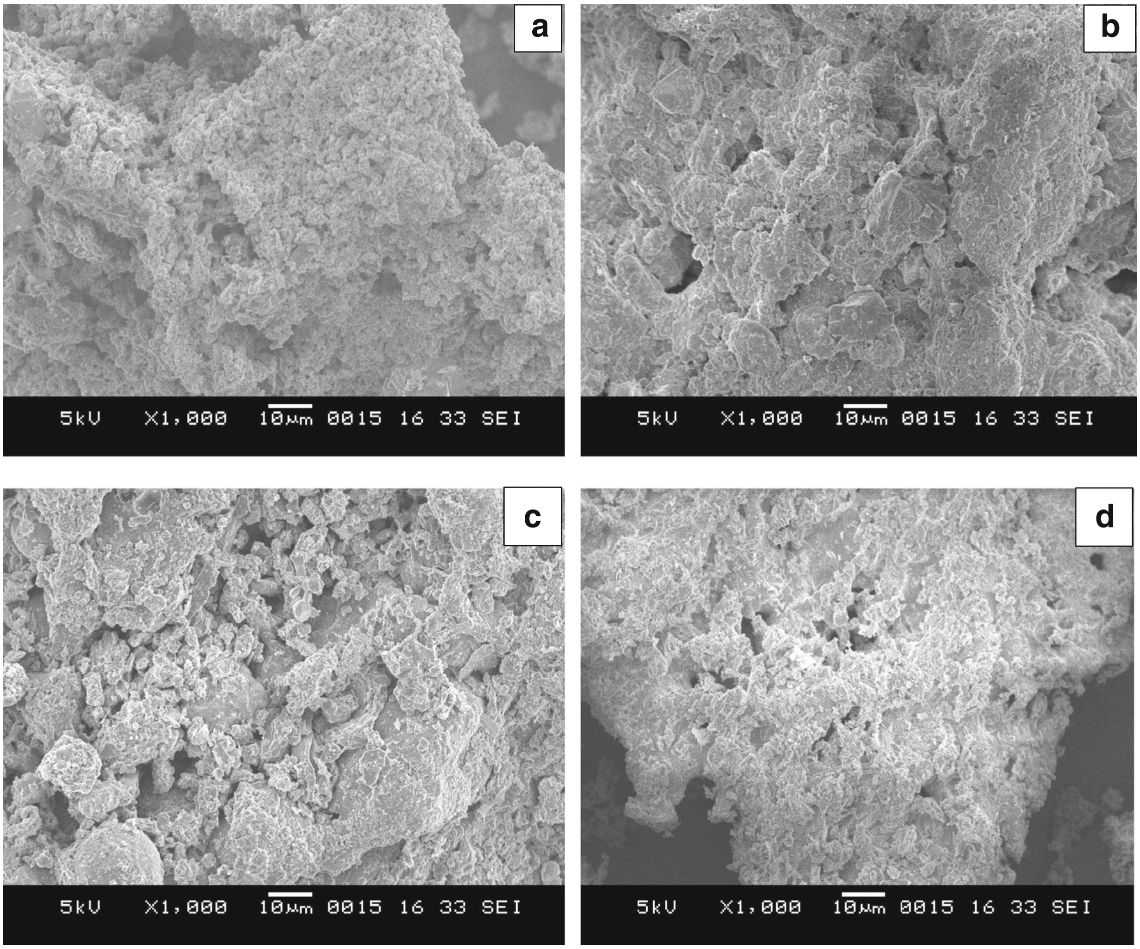

Fig. 3 Scanning electron micrograph of bottom ash produced during combustion of (**a**) C (**b**) G1 (**c**) G2 (**d**) G3

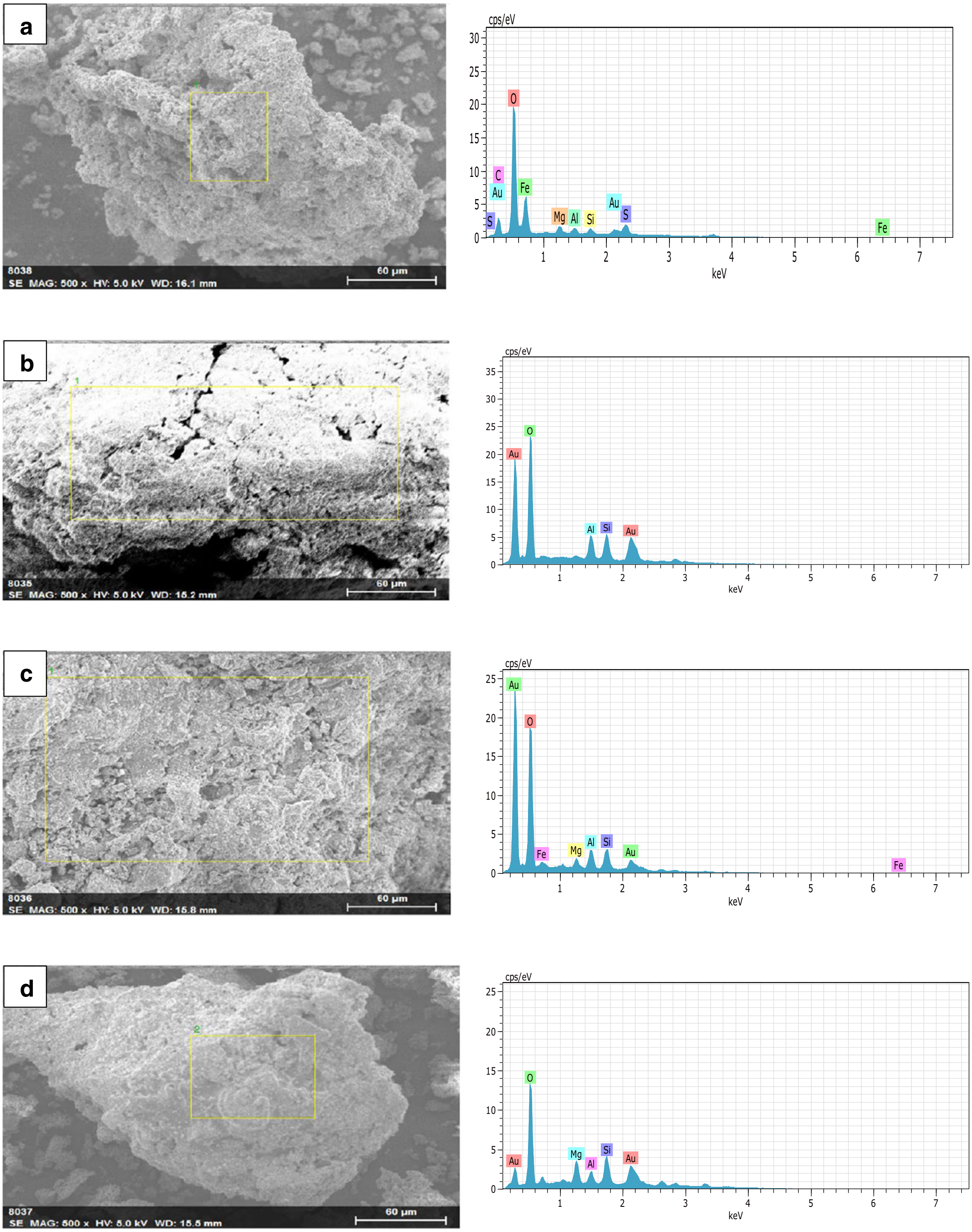

Fig. 4 EDX image and graph of bottom ash produced during combustion of **a** C, **b** G1, **c** G2, and **d** G3

The SEM images with the higher magnification (×1000) showed compositions with increasing SiO_2+Al_2O_3 compounds. On illustrating the SEM image of the bottom ash sample, its surface has numerous gradual materials and irregular shape particles. Also, the uneven distribution of material and slightly rough to smooth surface which is probably because sample experiences the higher temperature but improper combustion up to some extent (Kim and Lee 2015). It is evident from the main chemical composition of the bottom ash that it belongs to CaO-SiO_2-Al_2O_3-Fe_2O_3 system, which is similar to the common minerals admixture necessary in cement-based material. Compared to the coal sample, the bottom ash generated from the samples G1, G2, and G3 also showed nearly equal

Table 2 Concentration of different elements in bottom ash

Elements	Sample											
	C			G1			G2			G3		
	Normal (wt.%)	Atomic (wt.%)	Sigma (wt.%)	Normal (wt.%)	Atomic (wt.%)	Sigma (wt.%)	Normal (wt.%)	Atomic (wt.%)	Sigma (wt.%)	Normal (wt.%)	Atomic (wt.%)	Sigma (wt.%)
O	43.03	66.94	0.94	25.86	57.93	1.45	40.98	66.44	1.88	26.35	56.35	0.91
Si	0.33	0.29	0.03	18.85	24.06	0.44	20.80	19.21	0.41	23.10	28.14	0.32
Al	–	–		6.94	9.21	0.18	7.51	7.22	0.17	1.27	1.62	0.05
Fe	30.20	13.46	0.77	–	–	–	3.25	1.51	0.30	–	–	–
Mg	–	–		–	–	–	2.15	2.29	0.08	4.32	6.09	0.09

mineral composition contributing to the low LOI (%) which may be due to unborn particles in the sample (Li et al. 2012).

This is extremely interesting because Si and Al show a possibility to develop silicate crystal which can be further used in the cement or ceramic industry (Assi et al. 2020). The evaluation of silicate, aluminum oxide, iron oxide, and all the mineralogical content of the bottom ash was quantitatively analyzed using EDX. A typical composition for observed minerals in the coal and coal-mixed sludge sample is presented in Table 2. The quantity of mineral constituents of bottom ash produced through combustion of coal indicated the presence of hematite (0.77%) and quartz (0.03%). The combustion of coal-mixed sludge has shown the presence of mineral contents in bottom ash in percentage (w/w) as 0.32, 0.09, and 0.05 for quartz, MgO, and mullite, respectively. Thus, it can be concluded that bottom ash produced during the combustion of coal and coal-mixed sludge in a grate furnace clearly indicated the presence of quartz, mullite, and hematite (Malek et al. 2019).

The XRD analysis of ash produced from C, G1, G2, and G3 samples are shown in Fig. 5. It shows the presence of quartz (SiO), mullite ($3Al_2O_32SiO_2$ or $2Al_2O_3SiO_2$), and hematite (Fe_2O_3) (Alam et al. 2020). The prominent peaks of quartz in all the samples are in proximity at 22.15°, 27.23°, 50.18°, 60°, and 68.92° of 2θ of XRD graphs. Similarly, the prominent peak for mullite in all the samples has the proximity of 12.26°and 20.93°. Further, the peak of hematite in all the samples is in the proximity of 14.85°. The intensity of quartz was predominant in the sample which is correlated with utilization of bottom ash. The peak value of Al_2O_3 is slightly lower as it illustrates the active silicon dioxide and aluminum oxide in the sample (Torkittikul et al. 2017). The XRD peaks displayed the presence of Si, Al, and Fe which indicated that the bottom ash is suitable for use in the cement industry.

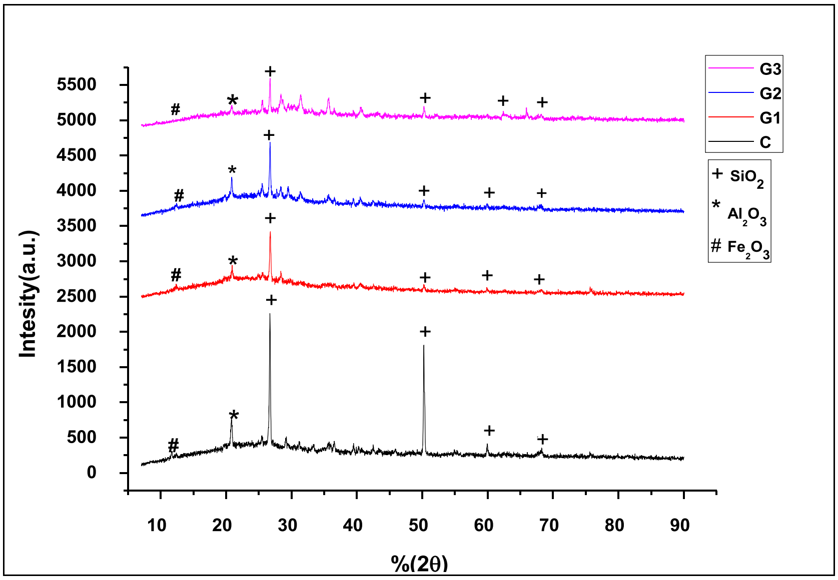

Fig. 5 XRD graph showing the presence of SiO_2, Al_2O_3, and Fe_2O_3 in bottom ash

Table 3 Concentration of metals in the leachate of bottom ash

Sl. No.	Metals	C (ppm)	G1 (ppm)	G2 (ppm)	G3 (ppm)
1	Al	0.64 ± 0.11	0.15 ± 0.13	0.55 ± 0.12	0.26 ± 0.11
2	Ba	0.06 ± 0.05	0.009 ± 0.06	0.16 ± 0.06	0.16 ± 0.07
3	Ca	3.47 ± 0.14	3.65 ± 0.11	3.47 ± 0.13	3.47 ± 0.11
7	Cu	BDL	0.03 ± 0.05	BDL	0.005 ± 0.01
8	Fe	0.14 ± 0.05	0.16 ± 0.06	0.06 ± 0.09	0.15 ± 0.1
11	Li	0.17 ± 0.01	BDL	0.07 ± 0.01	0.07 ± 0.01
12	Mg	77.76 ± 0.06	21.90 ± 0.09	24.22 ± 0.06	96.49 ± 0.05
13	Mn	0.26 ± 0.08	0.06 ± 0.09	BDL	0.09 ± 0.05
16	Sr	3.21 ± 0.12	0.21 ± 0.13	3.18 ± 0.16	1.84 ± 0.12
18	Zn	0.042 ± 0.08	0.014 ± 0.06	0.033 ± 0.04	0.03 ± 0.02

Characteristics of leachate generated from bottom ash

The results on the leaching test for the bottom ash indicated the presence of Al, Ba, Ca, Cu, Fe, Li, Mg, Mn, Sr, and Zn. The maximum leachable ion was Mg as its concentration in leachate is found to be in the range 21.90–96.49 ppm followed by calcium in the range 3.47–3.65 ppm. ICP-OES analysis of leachate of bottom ash generated during the combustion of coal-mixed sludge in different proportions in a grate furnace is presented in Table 3. Concentration of heavy metal is lower and reflected the fact that the bottom ash contains much fewer heavy metals and is usually considered non-hazardous waste. The leachability matrices are an important index to evaluate the absorption behavior and immobilizing effect. Leaching concentration is in the safety range and so on the basis of heavy metal concentration, bottom ash could be more reliable in the practical environment and can be used in various construction industries (Li et al. 2012).

Conclusion

The study clearly concluded that the distillery industries can utilize the sludge from the rehabilitated lagoon for co-combustion with coal in an existing boiler with appropriate modification, if required, in the current system. The combination G3, having burnout efficiency of 90.37%, was found optimum for its application. The bottom ash produced during the combustion of coal mixed sludge in different proportions has shown ignition loss at about 460°C. The mass loss peak indicated the dehydroxylation of C–H bond. The peak between 600 and 800°C was due to decarbonization of C–C bond, which is a valuable property to use. This ash is easily combined with calcium hydroxide to form the compounds required in cement industries. XRD analysis and other mineralogical properties (SEM and SEM-EDS) of bottom ash indicated that it is rich in calcium sulfate, aluminates, hematite, etc. As per the composition of the bottom ash produced, it stands as a sustainable alternative for use in cement industry as mineral additives, construction industry as partial replacement of concrete, and a base material in road construction. Environmental implications due to improper disposal and treatment of distillery sludge, i.e., contamination of ground water from generated leachate and bad odor production, etc. can be minimized in the present treatment process.

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Author contribution Lekha Dhote: formal analysis, investigation, data curation, software, and writing (original draft). Ram Avtar Pandey: visualization, validation, methodology, and writing (review and editing). Anirban Middey: data curation. Neel Kamal Mandal: data curation. Sunil Kumar: writing (review and editing), funding acquisition, and project administration.

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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