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Quantitative determination of energy potential of refuse derived fuel from the waste recovered from Indian landfill

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Abstract

Landfills are urban stocks and resource reservoirs for potential energy recovery. The purpose of this study is to evaluate the amount of energy that could be recovered from aged waste (around 5–20 yr old) recovered from landfills. Investigations were conducted on the physical and chemical properties of refuse-derived fuel (RDF) prepared from recovered landfill waste (RLW) in Andhra Pradesh, India. Waste characterization studies include determination of waste composition, proximate analysis, ultimate analysis, and energy content. The moisture content ranged between 25.7 to 31.3% and no trend was observed with age. In the ultimate analysis, the percentage of carbon increased from 42.9 to 71.7% with the age of the samples, this is due to an increase in the plastic content over time. The calorific value of the recovered landfill waste ranged from 10.4 to 21.8 MJ kg⁻¹. From the findings, it can be summarized that the RDF can potentially be utilized as a feedstock for the recovery of energy from RLW. The results from this study will assist policy makers and local authorities in designing and developing strategies for resource and energy recovery from landfills in different urban cities across the globe.

Keywords: Landfill recovered waste, Refuse derived fuel, Energy recovery, Incineration, Municipal solid waste, Calorific value, Plastic waste

Introduction

The amount of solid waste generated globally is expected to increase from 2010 t in 2016 to 3400 t by 2050 [1]. Population growth, rapid urbanization, demographic transfers, living habits, industrial, and economic developments are contributing factors to the increase in waste generation trends [2]. The handling, processing, treatment, and disposal of waste play a vital role in development of good solid waste management (SWM) systems [3]. In developing countries, it is estimated that municipal governments spend 20–50% of their annual budget on solid waste handling and management [1]. The cost benefit matrix in terms of resource recovery from solid waste is currently negative. It is also estimated that 80–

90% of waste in BRICS countries ends up in unlined landfill.

Figure 1 shows the waste generation and landfill disposal percentages in BRICS countries. The per capita generation rate is the highest in Brazil with 378 kg cap⁻¹ yr⁻¹ and the lowest is in India with 183 kg cap⁻¹ yr⁻¹. In Brazil and South Africa, 100% of the waste collected is dumped landfill. In India 91%, Russia 95% and China 79% of waste is disposed in a landfill [4]. Disposal of municipal solid waste (MSW) via unlined landfill is a common practice in low income and low-middle income countries. Unlined landfill waste is disposed in an unregulated approach leading to environmental and health hazards. In China, approximately 3000 t of MSW is disposed of to landfills over the last 30 yr. The Chinese national twelfth five-year plan of MSW treatment and management indicated a budget of USD 3.4 billion for landfill eco-remediation projects in China from 2011 to

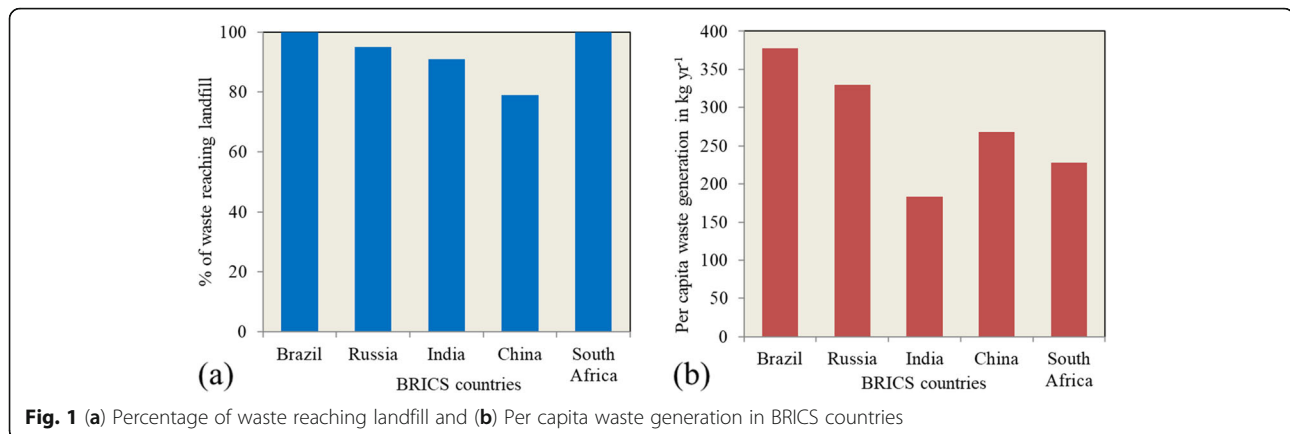
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2015 [5]. In Germany, about 2500 t of MSW has been disposed of to landfills since 1975. It is estimated that 250 t of combustible material, 26 t of iron, 0.85–1.2 t of copper and 0.5 t aluminum can be recovered from these landfills [6]. The waste dumped in the landfills should be considered as an urban stock and resource reservoir for future resource recovery [7]. In India, 62 Mt of waste is generated in the year 2016, 70% of waste generated is collected of which 22–28% is treated using biological (composting and anaerobic digestion) and thermal conversion methods (incineration) and the rest disposed of in landfills. With the present rate of dumping an area of about 1240 ha is required to dispose of waste in India alone [8, 9].

The development of new landfill poses a critical challenge for local authorities (municipal councils) and regulatory bodies given to economic constraints, environmental policies, and opposition from the community and scarcity of land resources. Councils are encouraged to plan and develop systems like source segregation, recycling, and energy recovery to reduce the environmental burden and increase the lifespan of landfill. An important challenge and critical job for councils is also the aftercare management of the closed landfill [10–15]. Characteristics and composition of landfill waste, geological and geo-technical properties, topography, climatic conditions and ground water flow conditions play a major role in the development of a management plan for landfill aftercare management. The lack of detailed records and databases poses a critical challenge in development of the management plan for leachate, odor, heavy metals, and methane control systems in developing countries [16].

Policies and environmental laws are being developed to create a methodology to extract resources and energy from the existing landfills [17, 18]. In India, consumption of energy has increased by 129% between 2000 and 2016. The forecasted annual growth rate of energy for India based on single-linear model to be 4.5–5.2% from 2017 to 2026 [19]. The energy mix of India is comprised

of coal (69%), hydro-power (14%), natural gas (10%), oil (4%), nuclear (2%), and renewable (1%). Energy demand is expected to double by 2035, posing a critical challenge on the sources, generation and supply of additional energy [20]. Global electricity production in 2016, increased by 2.9% reaching 25,082 tWh. Combustible fuels accounted for 67.4% of the total electricity production mix with 65.1% from fossil fuels and 2.3% from biofuels and waste. The remaining 32.6% came from hydroelectric plants (16.6%), nuclear power plants (10.4%), wind, tide, solar and other sources (5.6%). China (24.8%) and United States (17.2%) together account for 40% of total global electricity production. India (5.9%), Russian Federation (4.4%), Japan (4.2%), Canada (2.7%), Germany (2.6%), Brazil (2.3%), Korea (2.2%) and France (2.2%) including China and USA account for two-thirds of the global electricity generation [21]. In USA, electric power (37.1%), transportation (28.1%), industry (21.9%), residential and commercial uses (10.4%) are the major electricity consumption sectors [22].

A waste hierarchy was developed in India for efficient utilization of resources and to evaluate waste management systems to achieve the objectives of Waste Avoidance and Resource Recovery Act 2001. The waste hierarchy focuses on reducing the waste reaching landfill through the application of the 3R's (reduce, reuse and recycle), source segregation, and technical treatment of waste. Indian SWM regulations (2016) emphasize investigating the bio-mining and bio-remediation potential of old landfills [23–25]. In landfill mining, the old waste is excavated from the landfill sites for resource and energy recovery. Urban land reclamation, extraction of recyclables and waste derived fuels can be achieved through this process [25].

Landfill reclamation and mining research is being carried out globally to understand the technology, economic, and social constraints. Conceptual discussions, feasibility studies and pilot scale investigations are being performed to further understand the process of landfill mining for specified deposits. Composition and characterization

analysis are performed on the excavated waste samples based on age and location and are assessed to determine the energy and material recovery potential [26–32]. The waste composition in MSW landfill typically consists of 50–60% of soil-type material, 20–30% combustible components, 10% inorganic components, and a small amount of metals. The variation in the waste compositions from different landfill sites indicates that site specific investigations should be performed to quantitatively determine the material and energy recovery potential [7, 32]. The objective of this study is to determine the physico-chemical characteristics of the different aged-waste samples recovered from the landfill. Investigate the energy potential for refuse derived fuel (RDF) prepared from the combustible component to be utilized as a feed stock in thermal based waste to energy technologies.

Study area

The investigations were conducted in a landfill facility located 22 km away from Visakhapatnam city in Andhra Pradesh state, India, covering an area of about 38.5 ha. The landfill is an unlined facility receiving 1250 kt of solid waste on average per day. The landfill is in a small valley, surrounded by hills on three sides and a housing estate on the other. The landfill is 0.5 km away from a national highway (NH-16) and it is within 5 km radius of a coastal zone (Bay of Bengal). Waste has been dumped at this unlined landfill site for the past 20 yr. The average depth of the waste heap from the top of the waste varies from 10 to 12 m in the sample collection area. The study area and sampling locations are shown in Fig. 2.

Sample collection

The sample collection methodology was determined in accordance with American Society for Testing and Materials (ASTM) D6009–12 (Sampling Waste Piles) [33] and the number of samples was determined as per ASTM D5321–92 (Reapproved in 2016) [34]. The location for the sample collection was determined through personal interview with the working staff. The samples were collected based on the age of the waste from the sample locations. Figure 2 represents the satellite imagery of the landfill and sample collection area. The age of the waste in sampling location L1 (shown in Fig. 2), varies between 10 to 15 yr (S1). The age of the waste in sampling location L2 varies between 5 and 10 yr (S2) and in L3 is less than 5 yr (S3). A trenching method was followed to collect the samples from the different depths. Trenches were dug using a bulldozer with a backhoe loader. The height of the waste heap varied between 10 to 12 m in all the three sampling locations. Initially the top layer containing soil and plants were removed to a depth of 0.20 m. At every sampling location, 18 samples of 10.0 ± 0.2 kg each were collected from three depths at a step interval of 2 m. Overall, 500 ± 25 kg sample was collected for each sampling location. This process of sampling was adopted to replicate the field practices being followed by a collaborating firm associated with council in the development of a waste-to-energy plant.

RDF sample preparation

The samples collected were initially sieved through the 4.75 mm sieve to segregate the inert material. Retained sample waste mixed and placed in hot air oven for a period of 24–48 h at 70 ± 2 °C. Dried samples were



Fig. 2 Study area and sampling locations in the landfill, Visakhapatnam city

sieved in a mechanical sieve shaker for 15 min and further hand sorted to segregate the waste into different components. The components are inert material (soil and stones), combustibles (plastics and textile), inorganic (ceramics, glass and metal), and others (wood, coconut residues and bones). The weight of each component was then determined and a pie chart for physical composition of waste samples was developed. Segregated combustible components from each sampling location were mixed to prepare a representative RDF sample. The representative RDF samples (S1) and (S2) were prepared from the combustible component representing 10–15-yr-old samples and 05–10-yr-old samples. An RDF sample (S3) representing 0–5-yr aged sample was prepared by mixing combustible components (plastic and textiles) and coconut residues. The samples were shredded to achieve a size of 1.0 ± 0.5 cm to perform the experimental studies. All the experiments were performed in triplicates. The initial sample (sample from landfill) and final sample (prepared for sample analysis) are shown in Fig. 3.

Analysis methods

Proximity analysis was performed to determine the moisture content, volatile solids, fixed solids and ash content. Moisture content of the samples was determined in accordance with ASTM E1756–08 [35]. During sampling process, nine samples of 1 kg each were collected using stratified random sampling procedure to prepare a representative sample for determining moisture content. The samples were packed and sealed to reduce the interaction with ambient environment. The samples were transferred to the laboratory within 2.5 ± 0.5 h and placed in a hot air oven for a period of 24–48 h to determine the moisture content.

The volatile combustible matter was determined in accordance with ASTM E872–82 [36]. Silica crucibles containing the samples were covered with lids and they were placed in a thermostatically controlled muffle

furnace at a temperature of 550 ± 20 °C for a period of 120 min to determine the quantity of volatile solids. The ash content was determined in accordance with ASTM D1102–84 [37]. Silica crucibles without lids were placed in the muffle furnace at a temperature of 550 ± 20 °C for a period of 30 min.

For the elemental analysis, the samples were shredded to a size less than 600 μ m. The shredded samples were dried in a hot air oven at a temperature of 103 ± 2 °C for a period of 24 h to remove the moisture content. The elemental composition of the sample was determined using a Euro Vector A3000 elemental analyzer. During sample preparation for elemental analysis, the attached soil-like material was removed and the samples were shredded both mechanically and manually to the desired size. The samples were mixed well to achieve a homogeneous nature. Systematic random sampling was used for preparing the final sample to ensure the presence of multi components. The mixed sample was spread over a petri dish and it was divided into four parts. From each part sample was collected to prepare final sample for analysis. The analysis was performed five times in triplicate for each representative sample.

The calorific value of the samples was determined in accordance with ASTM E711–87 [38]. Pellets of weight 1.0 ± 0.5 g were prepared from the RDF samples using a hand pelletizer. The pellets were then placed in an adiabatic bomb calorimeter. The initial temperature and the final temperature were recorded for the determination the energy content.

Heavy metal analysis was performed to determine the amount copper, lead and cadmium in the ash. About 0.5 g sample was acid digested using HNO_3 and HCl acid mix (1:3 M ratio). The digestion process was performed in accordance with procedure outlined in USEPA 3050B:1986 [39]. The final sample for analysis was prepared by passing digested sample through

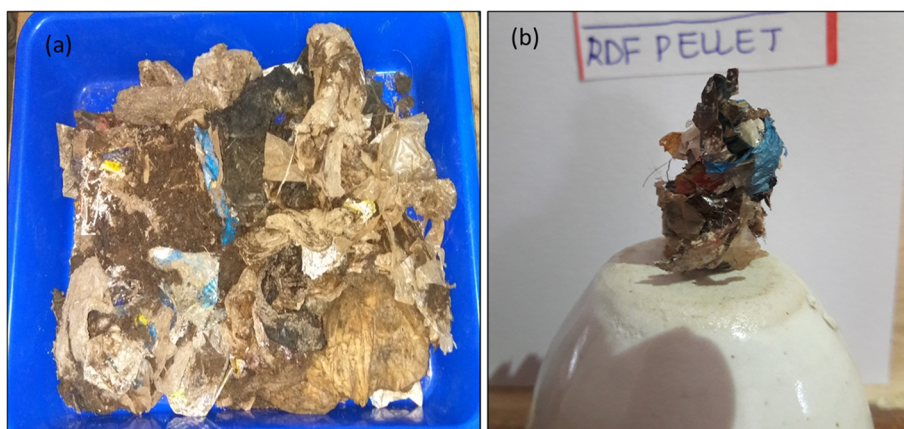


Fig. 3 (a) Initial sample (sample from landfill) and (b) Final sample (prepared sample for analysis)

Table 1 Moisture content analysis of the aged waste recovered from landfill

Parameter	Unit	S1 (n = 7)	S2 (n = 7)	S3 (n = 7)
Moisture content	% weight	26.4 ± (0.7)	28.7 ± (0.8)	30.9 ± (0.6)

Value in parenthesis represent *standard deviation*

Whatman No. 42 filter paper. The heavy metals were analysed using atomic absorption spectrophotometer.

Results and discussion

Moisture content

Moisture content for the three samples ranged between 25 to 31% and is represented in the Table 1. Moisture content was high in sample S3 (30.9 ± 0.6%) and lowest in the sample S1 (26.4 ± 0.7%). It was observed that moisture content increased with age and depth of the samples. The sample collection was conducted during the pre-monsoon season. The weather conditions were humid and hot with an average temperature ranging between 35 to 40 °C. Initial showers occurred for short duration. The moisture content value is associated with amount of precipitation, percolation of water in waste piles, water holding capacity, and degradation activity of the organic waste [7]. A two-way ANOVA test indicated that there is no significant difference ($p > 0.05$) in the moisture content obtained from the different age and depth samples.

For incineration, moisture content of the feedstock should be less than 45% [40]. In India, the average moisture content was ranging from 31 to 65%. The percentage varies due the composition, seasonal variations, and climatic conditions. During the incineration plant design for mixed waste, secondary pit has to be designed to drain leachate under gravity. The leachate has to be collected and treated for disposal or application on land. Comingling of wastes with different moisture content is an alternative approach for reducing moisture in waste. For the aged waste, the combustible components (plastic and textile) are contaminated with soil-type material. Pre-heating followed by cleaning systems should be

designed to remove moisture content and soil-type material. The percentage of moisture content is one of the critical parameters in the design of drying unit.

Physical composition of the waste

The mean percentage of waste composition (by dry weight) for the samples collected from the unlined landfill in the study area is represented in Table 2. It was observed that the soil-like material trends increase with the age of the sample. Drain silt and street sweeping waste are mixed with the waste leading to an increase in soil waste levels. High amount of ash is observed as the rag pickers at the dumping site burning the heaps of waste to recover metal and ferrous material. The plastic waste component of the waste also increases with the age of the waste. It was probably due to increase in the usage of the plastic products after 2000 [42]. The annual per capita plastic product consumption in India is estimated as 11 kg [43]. Plastic is one of the major components that can be harvested from a landfill. The plastic component mainly includes covers, wrappers and 3D films. Water bottles and recoverable plastics are being picked up by the rag pickers for recycling.

Glass, metal and ceramics are being collected by the rag pickers. The organic waste, paper, yard waste and other biodegradable wastes decompose under anaerobic conditions leading to the release of methane gas. In the aged samples 95% of the biodegradable component is decomposed. Table 2 also presents a comparative study on physical classification of the aged waste recovered from landfill. Two-way ANOVA showed a significant difference ($p < 0.05$) in soil-type material, plastics and textile among all waste samples. No significant difference ($p > 0.05$) between S1 and S2 was observed for glass, metal, and ceramics.

Composition of landfill waste varies based on geographic location, socio-economic conditions, dietary habits, seasonal variations, recycling rates, and informal sector activity. Designing a system based on the average

Table 2 Physical classification of the aged waste recovered (in %) from landfills

Location	Visakhapatnam, India (This study)			Thailand [31]				Belgium [41]	Thailand [32]
	10–15 S1 (n = 7)	5–10 S2 (n = 7)	< 5 S3 (n = 7)	2	5	7	10	14–29	3–5
Soil-like material (%)	56.6	53.7	45.9	32.9	56.5	27.8	49.1	44 ± (12)	34
Paper (%)	–	–	2.3	4.1	–	–	–	7.5 ± (6)	3.3
Plastics (%)	23.1	18.6	16.8	36.7	24.6	44.8	35.3	17 ± (10)	31
Textile (%)	2.7	5.8	10.4	11.5	7.4	10.2	1.8	6.8 ± (6)	7.6
Glass (%)	4.4	4.3	3.5	1.7	4.1	1.2	4.7	1.3 ± (0.8)	6.5
Ceramics (%)	4.9	4.7	2.4	1.1	0.8	0.7	2.9	–	–
Metal (%)	4.9	4.2	2.9	1.7	1.7	3.3	4.4	2.8 ± (1)	6.4
Others (%)	3.4	8.7	15.8	10.3	4.9	11.8	1.8	16.7	11.2

“–” Not Detected; Value in parenthesis represent *standard deviation*

Table 3 Proximate analysis of the aged waste recovered from landfills

Parameter	Unit	Present study			India [44]	China [7]
		S1 (n = 9)	S2 (n = 9)	S3 (n = 9)		
Volatile solids	%	58.6 ± (1.3)	51.7 ± (0.8)	43.7 ± (0.3)	45.3	87.1 ± (1.1)
Ash	%	11.6 ± (0.3)	13.7 ± (0.2)	17.4 ± (0.4)	24.7	10.4 ± (0.3)
Fixed solids	%	3.3 ± (0.6)	5.9 ± (0.8)	8.1 ± (0.6)	4.5	2.1 ± (0.4)

The summation of the values represents total solids. Addition of moisture content will sum up to 100. Value in parenthesis represent *standard deviation*

composition values will reduce the efficiency of the plant. Physical composition of the landfill waste plays a pivotal role in designing an incineration unit to meet the needs of local conditions.

Proximate analysis

The proximate analysis results of the RDF samples are presented in Table 3. RDF sample (S1) had high volatile solids of 58.8 ± (1.3)% dry weight and low ash content of 11.6 ± (0.3)% dry weight and fixed carbon content of 3.2 ± (0.7)% dry weight as compared to other RDF samples. In the RDF samples the volatile matter ranged between 43 and 58% on a dry weight basis. The decrease in volatile matter from RDF Sample S1 to S3 suggests that the organic matter decreases with the age of the waste. Central pollution control board compiled a report on selection criteria for waste processing technologies [40]. For incineration, the volatile matter should be greater than 45%. In RDF samples S1 and S2 the volatile matter is higher than 45% while in S3 sample the volatile matter is 2.5 to 4.0% less compared to the desired value. The ash content of the RDF samples ranged between 11 and 18% on a dry weight basis. The permissible range of ash content to achieve high efficiencies in mass burning incinerators recommended by US Environment Protection Agency is 5–15% (dry basis). In RDF samples S1 and S2 the ash content is within the range while in S3 sample the ash content is 13–18% higher than the maximum permissible value. The fixed carbon ranged between 3 and 9% on a dry weight basis. The high percentage of fixed carbon indicates longer retention times for combustion in incinerator [44].

The volatile solids content of normal plastic (not landfill recovered) is 98.5%, the ash content is 1.2% and the fixed carbon less than 0.1% [7]. In the present study, the representative samples of RDF were prepared without pretreatment for landfill mined plastic and textile components. The impurities attached to the surface are not completely removed. The inert material and impurities from the landfill recovered waste components can be reduced through a suitable pre-cleaning method during the RDF sample preparation. This will increase the volatile solids, heating value and reduces the ash content of the RDF. Table 3 presents the results obtained and comparative analysis of proximate analysis. The results

obtained in the present study are within the range obtained from other similar researches [7, 44].

Ultimate analysis

The ultimate analysis results of the RDF samples are presented in Table 4. RDF sample (S1) has a high percentage of carbon 71.7 ± (13.7)% dry weight as compared to other RDF samples due to the amount of plastic content. No trend was observed for the plastic waste with age of the samples. The amount of plastic content in the waste depends on the consumption rates, disposal practices and recycling systems in the urban cities. Site specific characterization studies provide in depth understanding on the plastic waste component across the globe. Compared to normal plastic waste, recovered plastic waste has lower carbon content attributed to the presence of impurities like soil, sand that are difficult to be cleaned.

In RDF samples S2 and S3 the percentage of sulphur was 24.6 ± (3.0)% and 33.0 ± (10.5)% on a dry weight basis. The values obtained in this study are representing a high value of sulphur content compared to the other studies in literature. The high amount of sulphur is attributed to the formation of oxides of sulphur, hydrogen sulphide and volatile malodorous organic compounds with the aerobic and anaerobic decomposition of the waste. During ageing process in landfill, organic material with low molecular weight is degraded and resistant materials are converted to humus-like matter. In this, transformation process the redox buffer changes from reducing conditions to slightly oxidizing conditions creating a favorable condition for sulphide to dissolve. The leaching experiments showed that the sulphur content is high in aerated landfill compared to original landfill indicating dissolution of sulphide in landfill material is a slow process. Binding of sulphide with solid landfill material due to deposited sulphur has been reported [45].

The percentage of oxygen in all the samples ranged from 9 to 12%. The percentage of hydrogen and nitrogen was low. The percentage of hydrogen decreased with the age of the waste and no trend was observed in terms of nitrogen and oxygen content.

Calorific value

The calorific value results of the RDF samples are presented in the Table 5. The High Heating Value (HHV)

Table 4 Ultimate analysis of the aged waste recovered from landfills

Parameter	Unit	S1 (n = 5)	S2 (n = 5)	S3 (n = 5)	Literature [6]
Carbon	%	71.6 ± (13.7)	57.5 ± (16.8)	42.9 ± (9.6)	40–75
Hydrogen	%	0.9 ± (1.9)	1.5 ± (2.9)	2.3 ± (2.2)	4.9–9.8
Nitrogen	%	0.8 ± (1.1)	0.2 ± (0.3)	1.1 ± (0.7)	0.03–4.1
Sulfur	%	1.4 ± (0.8)	24.6 ± (3.1)	32.9 ± (10.5)	0.1–0.5
Oxygen	%	9.4	9.1	11.5	–

Value in parenthesis represent *standard deviation*

on a dry basis was found to be the highest for the RDF sample (S1) or $20.5 \pm (2.9) \text{ MJ kg}^{-1}$ and lowest for the RDF sample (S3) of $11.1 \pm (0.7) \text{ MJ kg}^{-1}$. The variations were due to the physical composition of the samples. Using Dulong's equation and elemental composition, HHV (theoretical) was determined for the RDF samples. The HHV (experimental) and HHV (theoretical) for the RDF sample (S3) were found to be matching. However, for the other two RDF samples a percentage variation of 5–15% was observed. As per SWM rules 2016, RDF samples prepared from solid waste are recommended to be utilized as fuel in incineration units, if the calorific value is greater than 6.3 MJ kg^{-1} . In the present study, the calorific value of all the three RDF samples prepared from the waste recovered from landfill can be used as a feedstock in mass burn incineration plant. Table 5 presents the results obtained and comparative analysis of energy content. The results obtained in the present study are within the range obtained from similar researches [7, 40]. The calorific value of landfill recovered waste depends on the composition of the waste and percentage of impurities. In the present study, segregation of the waste in laboratory contributed to high calorific value. However, pre-cleaning was not performed to simulate current field practices. The average calorific value of the plastic material is 43.6 MJ kg^{-1} [7]. The calorific values obtained in this study are low compared to the normal plastics. Segregation and pre-cleaning of recovered waste will increase the calorific value of the RDF. Development of pre-treatment systems involves high capital and operation costs and requires skilled personal for operation and maintenance [46].

The recovered landfill waste can be utilized to develop RDF or directly incinerated to harness thermal energy using the advancements in current technologies. RDF can mix with sawdust, rice husk, plastic waste, and other combustible components in certain ratio to increase the calorific value of feedstock. According to previous researchers, thermal treatment options are economical compared to chemical recycling methods [7]. Life cycle assessment studies should be conducted on designed treatment systems to develop environmentally sound solution [47, 48].

Heavy metal analysis in ash

The amount of copper, lead and cadmium in the water extract of ash samples are shown in Table 6. The ash generated is disposed into the landfill located 4 km from the waste to energy unit. The landfill is single liner facility, precautionary measures to identify leaching of heavy metals to be installed to protect soil and ground water from contamination. Assessment of heavy metals in ash and volatile gases plays a pivotal role in determining the application of RDF as source of fuel in industrial applications. The presence of heavy metals in RDF contributes to variations in mechanical properties and reactivity characteristics. The major sources of heavy metals include leather, power wires, metal cans and scrap material [49].

Conclusions

The present study investigated the energy potential of landfill recovered waste based on the physico-chemical characteristics of the waste. Based on physical composition, soil-like material, and plastic (waste plastic bags and foils) are the major components of the aged waste recovered from landfill. The moisture content and the percentage of

Table 5 Energy content analysis of the aged waste recovered from landfills

Parameter	Unit	Present study			India [44]	China [7]
		S1 (n = 3)	S2 (n = 3)	S3 (n = 3)		
HHV (Exp)	MJ kg^{-1}	$20.5 \pm (2.9)$	$16.8 \pm (1.6)$	$11.1 \pm (0.7)$	10.7	$44.8 \pm (1.2)$
HHV (Th)	MJ kg^{-1}	22.5	19.6	11.8		

Value in parenthesis represent *standard deviation*

Table 6 Heavy metals analysis in ash

Heavy metal	Unit	Copper (n = 3)	Cadmium (n = 3)	Lead (n = 3)	Zinc (n = 3)
Value	$\mu\text{g kg}^{-1}$	105.8 \pm (32.1)	1.8 \pm (0.9)	39.6 \pm (11.4)	166.2 \pm (36.5)

Value in parenthesis represent *standard deviation*

contamination increased with the age of the waste. Comparing the physico-chemical characteristics of landfill mined waste with process input criteria; incineration of RDF is best possible thermal conversion approach. The RDF prepared from the combustible component (plastic and textile) and coconut shells can be utilized as fuel source with proper pre-cleaning. The volatile solids, ash content and energy content analysis highlight that the adoption of pre-cleaning techniques such as cleaning, drying, and sorting, must be implemented to remove the impurities on the surface of the recovered waste feed stock. The treatment technologies options (gasification, pyrolysis, hydrothermal carbonization) can be explored by using comingled feed stocks. Overall, landfills can be considered as resource reservoirs for future energy generation. Reclamation of the waste material from these landfills increases the life of the landfill and reduces the usage of non-renewable energy sources in energy production. Composition and characteristics of aged waste play a key role in designing the treatment systems for waste recovered from landfill.

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Authors' contributions

VRS has conducted field studies, laboratory analysis, interpretation, and written the draft manuscript. MJ and BD have curated data and revised the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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