Waste Management 85 (2019) 151–163

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Environmental burden by an open dumpsite in urban India

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ARTICLE INFO

Article history:
Received 6 August 2018
Revised 15 December 2018
Accepted 18 December 2018

Keywords:
Dumpsite
Municipal solid waste
Energy content
Gaseous emissions
Spontaneous fire

ABSTRACT

Open municipal solid waste (MSW) dumpsites are nowadays looming hotspots for water, air, and land pollution. Fresh and old MSW samples collected from a dumpsite in the coastal city of India were analyzed for moisture content, volatile content, energy content, elements, and toxic heavy metals. The compositional analysis results showed that fresh MSW consisted of 36% by weight bio-waste (food waste, yard waste, coconut waste) and around 30% recyclable materials (plastics, paper, cardboard, and metals). Approximately, 62% of the total fresh MSW was found to be combustible materials (plastics, paper, textile, rubber, cardboard, yard waste, and coconut husks). The analysis of old MSW samples collected from different depths (3–4 m and 6–7 m) showed the dominance of plastics (25–33%) and mixed residue (28–55%) having high energy content. Measurements of gaseous emission below 6–7 m from the surface indicated a higher concentration of methane (CH_4:5.85 ± 0.12%) and lower concentration of carbon monoxide (CO: 3.82 ± 1.3 ppm), and hydrogen sulfide (H_2S:10.15 ± 2.2 ppm). Haphazard dumping, waste characteristics, waste pile compaction processes and heat propagation due to deliberate fire may stimulate spontaneous fires.

1. Introduction

The unprecedented population growth along with improving living standards in lower middle-income countries (LMIC) has caused a significant challenge in the handling of huge quantities of municipal solid waste (MSW) generated per day. MSW disposal through open dumping is still being practiced in many countries across the globe. Dumpsites are open lands where MSW is discarded haphazardly. In India, municipal solid waste management has emerged as one of the challenges not only for the aesthetic look of a city but also for the environment and public health. Approximately, 1,43,449 metric tons of waste generated per day in India during 2014–2015, with an average of 0.11 kg per capita per day (Kgs/capita/day) (CPHEEO and MOUD, 2016). Nearly 40% of the total MSW generated is disposed of in open dumpsites which serve around 3–5% of the world's population (Mavropoulos and Newman, 2015). Due to the expansion of cities, waste disposal sites have become part of the city and ascended as one of the major concerns of environmental impacts and public health.

The waste stream in the old dumpsites is commingled organic and inorganic waste indicating the inefficiency in source segregated collection and transport. MSW characterization is one of the crucial information required for the sustainable management system of MSW (Al-khatib et al., 2010). It also helps to quantify the potential materials recovery, identify the source generation, and analyze the physical, chemical, and thermal properties. Moreover, physical and chemical attributes of the MSW are essential parameters to estimate material recovery and to diversify the viable treatment options based on the distribution of waste streams among combustible, compostable, recyclable (Qing et al., 2010).

In the present study, an attempt has been made to understand the characteristics of fresh and old MSW from an open dumpsite located in a tropical urban area. Further, the present study also discusses a holistic approach for management of fresh and old MSW to reduce the burden of open dumpsite on the surrounding environment and public health.

2. Spontaneous fire events in open dumpsite

Past studies have reported environment concerns of dumpsites such as groundwater and soil contamination by leachate, the release of substantial quantities of greenhouse gases (Banuraman and Madavan, 2011; Kumar et al., 2015). Wiedinmyer et al. (2014) estimated that nearly 2 billion metric ton of garbage generated each year globally and half of which was subjected to open burning. The existing dumpsites in Indian cities are overloaded with the large quantity of organic waste. Heaps of wastes in open

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https://doi.org/10.1016/j.wasman.2018.12.022
0956-053X/

dumpsites are generally trapped with inflammable biogases and are vulnerable hotspots for spontaneous fire events. There are reported fire incidents in dumpsite causing severe air pollution and consequent respiratory distress (The Hindu, 2012). Often, the population residing in the neighborhood of the dumpsite is exposed to hazardous pollutants emitted from the spontaneous/deliberate fires at the dumpsite.

Lack of inspection and tracking of the incoming non-segregated waste streams have resulted in the uncontrolled disposal of waste at the dumpsites leading to spontaneous fire hazards. Further, the deliberate burning initiated by informal waste collectors or operators to recover the valuable materials and to reduce bulk volume of MSW, respectively are quite common in developing countries (Kumar et al., 2015; Vreeland et al., 2016). The spontaneous fires in open MSW dumpsites are generally occurring due to the complex mechanisms involving interactions between oxygen (O_2: air ingress), combustible waste materials (fuel), and heat formed by biotic and abiotic processes (Buggeln and Rynk, 2002; Copping et al., 2007; Moqbel, 2009). Spontaneous combustion (SC) is defined as the combustion of material in the absence of an externally applied spark or flame, that is, forced ignition (Buggeln and Rynk, 2002). However, the identification of combustible waste materials responsible for spontaneous fires is seldom investigated.

Dumpsites contain a mixture of MSW components which have different thermal characteristics that can initiate self-combustion. Kayser and Boyars (1975) reported that some of the organic waste components, for example, paper, rags, textiles, scrap rubber and yard waste which can be easily subjected to SC under preferable conditions. Moqbel et al. (2010) conducted laboratory experiments and evaluated the effect of moisture, oxygen concentration and leachate on the self-ignition of MSW components. Amongst fire hazards, subsurface fires by spontaneous combustion are considered to be the most dangerous and devastating ones. Temperature, aging, MSW composition and its properties are key factors affecting SC. These factors vary across the MSW disposal facilities because of the heterogeneous nature of MSW. Thus it is important to understand the characteristics of MSW components which are susceptible to spontaneous combustion, especially in tropical climatic conditions. The present study aims to understand the likely influence of the characteristics of MSW on SC and provide the key information required for the prevention of SC.

3. Materials and methods

3.1. Study area

Chennai is the capital city of Tamil Nadu and the fourth largest Metropolitan City in India with a population of 9.88 million. Chennai city receives a considerable amount of rainfall during the South-West monsoon because of sea-breeze induced convections. Predominant winds in Chennai are usually southwesterly between April and October and northeasterly during the rest of the year. The maximum temperatures around 35–40 °C are recorded in March-early June, while December and January with minimum temperatures of 19–25 °C.

Waste-to-Energy Research and Technology (WTERT) Council data showed that Chennai city generates approximately 6404 metric ton of MSW per day with highest per capita waste generation rate of 0.77 kg in India (Times of India, 2014). Greater Chennai Corporation has divided the city into three regions, namely North, Central, and South, with five zones each, thereby making a total of 15 zones for administrative purposes. The daily generated MSW is being dumped into two major dumpsites –Kodungaiyur and Perungudi. MSW collected from zones 1 to 8 are being dumped at Kodungaiyur dumpsite in northern Chennai whereas MSW from zones 9 to 15, dumped at Perungudi dumpsite in southern Chennai (Fig. 1). Perungudi dumpsite is one of the oldest dumpsites in the city with a disposal rate of approximately 2200–2400 tons per day. The height of dumpsite is around 10–15 m. The dumpsite is constantly in the regional news for fire hazards due to the spontaneous or deliberate burning of garbage even though it is banned in India. The entire area of Perungudi dumpsite is spread over the Pallaikarnai marshland which holds unique ecological and economic importance. This dumpsite is in proximity to the residential area of Perungudi with an estimated population of 43,111.

A tropical climate with higher temperature and humidity significantly influences the impacts of dumpsite on the surrounding environment. The open dumpsites are subjected to air intrusion and rain events which enhances the biological and chemical oxidation of organic waste materials over a period of time. This results in further increasing the temperature of waste piles which can stimulate spontaneous fire events (Buggeln and Rynk, 2002).

3.2. MSW sample collection and gaseous emission measurements at the dumpsite

MSW is heterogeneous and consists of different waste components, requiring multiple samples at various locations in the dumpsite to understand its characteristics. Among different locations at the dumpsite, two locations (site 1and site 2) were selected based on the images of temperature profile measured using thermal imager (Fluke Ti105, Fluke Technologies Pvt. Ltd. India). Fluke thermal imager works on the principle of infra-red radiation detection and subsequently creates the thermal image. It has a sensitivity of ±2 °C with a temperature measurement range of −20 °C to +250 °C. The temperature at multiple points of each depth was measured by a thermometer (REOTEMP Instruments, San Diego, CA) while digging and collecting MSW samples. Quartering and coning method were adopted for the collection of both fresh and old MSW samples. Backhoe excavator was used to collect the 50 Kg of MSW samples at different depths of 0–1 m, 3–4 m, and 6–7 m. Approximately, 100–120 kg of 2 set of fresh MSW samples were collected manually. The collected samples were stored in air-tight plastic bags and transported to the laboratory for the analysis of physical and chemical properties. The waste samples were segregated manually into different components such as putrescible, combustible and recyclable waste in the laboratory. The old waste components had a size of less than 10 cm. The descriptions of waste components collected at dumpsite are presented in Table A.1.

At dumpsites, three boreholes were drilled by 2-inch hollow stem augers at 10 m depth to measure gaseous emissions. Gas samples were measured by using a portable multi-gas analyzer (Area RAE Steel, Rae Systems by Honeywell) for methane (CH_4) (1 to 100% LEL ± 1% LEL), carbon monoxide (CO) (10 to 2000 ppm ± 10 ppm), and hydrogen sulfide (H_2S) (0 to 100 ppm ± 1 ppm). Gas samples were collected by inserting the sampling probe at the surface, 3–4 m and 6–7 m for 20 mins.

3.3. Proximate, ultimate and heavy metal analysis of MSW samples

Moisture content (MC) of MSW components was determined by drying of samples to a constant weight in an oven at 100–105 °C for 24 h (APHA, 2005). Volatile solid (VS) in each MSW component was determined by igniting dried samples at 550 °C for 1 h (Peces et al., 2014; Telliard, 2001). A CHNS analyzer (Vario EI cube, Elementar Analysensysteme GmbH, Germany) was used to estimate the weight percentage of elements- carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) present in the MSW components. The high heating value of MSW components was measured by the adiabatic oxygen bomb calorimeter (IKA C2000 bomb calorimeter,

Fig. 1. The open MSW dumpsite located in Southern Chennai, India.

Analysentechnik GmbH, Germany). Low heating value (LHV) of MSW samples can be calculated by the following equation (Franjo et al., 1992).

$$LHV_w = HHV_d(1 - MC) - 2440(MC + 9H) \quad (1)$$

where HHV_d = higher heating value (KJ/dry kg), which is obtained from bomb calorimeter; MC = moisture content of MSW samples and 9H = final mass of water formed by hydrogen percentage present in MSW samples and 2440 = latent heat of the vaporization of water at 25 °C (KJ/kg).

Heavy metals in MSW components were extracted by using a closed vessel microwave acid digestion (Multiwave Go, Anton Paar GmbH) and analyzed for aluminum (Al), arsenic (As), boron (B), barium (Ba), calcium (Ca), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), selenium (Se), vanadium (V) and zinc (Zn) by ICP-OES instrument (Perkin Elmer Optima 5300 DV). All MSW samples were analyzed in five times, and the mean values were used to minimize errors in the result. The detailed analytical procedures of CHNS analysis, energy content and heavy metal analysis are provided in supplementary material.

3.4. Statistical analysis

Non-parametric Spearman correlation analysis and one-way analysis of variance (ANOVA) of MC, VC, HHV, LHV, and CHNSO were performed by the statistical package for the social sciences (SPSS) (Version 21). One- way ANOVA was performed at statistical significance level α of 0.05 to analyze the characteristics of MSW components collected at different depths. If the significance P was larger than α, there was no significant difference in properties of MSW components; when significance P was smaller than α, a substantial difference existed among MSW components collected at different depths.

4. Results and discussion

4.1. The present scenario in the dumpsite

Two old waste heaps were selected based on temperature which is one of the crucial factors for self-ignition. Fig. 2a and b show the temperature of waste heaps at the dumpsite. The temperatures were recorded at site 1 and site 2 as 61.7 °C and 50.3 °C, respectively. The average temperatures of waste heap were recorded on site 1 (at surface- 39.13 ± 1.03 °C, at 3–4 m below – 63 ± 0.22 °C and at 6–7 m below – 54.4 ± 0.7 °C) and site 2 (at surface- 39.56 ± 0.5 °C, at 3–4 m below – 53 ± 0.65 °C and at 6–7 m below – 49 ± 0.62 °C). The MSW composition in the dumpsite consisted of commingled biodegradable and recyclable waste components showing inefficient source-based segregation practice in the city. The metal scrap burning by the informal sector (rag pickers and waste pickers) is frequently observed in the dumpsite, releasing THMs into the atmosphere. The waste pile compaction processes and use of soil, construction and demolition waste as cover on dumped wastes are still practiced at the dumpsite.

4.2. MSW composition

The hand-sorted waste components of collected fresh MSW samples are shown in Fig. 3a. The organic waste components such as food waste, coconut shells and husks and yard waste constitute a major portion (35%) of collected fresh MSW samples from the dumpsite. MSW characterization studies in developing countries reported that organic fraction constituted major portion (40–45%) of total MSW stream (Al-khatib et al., 2010; Baawain et al., 2017; Miezah et al., 2015; Quaghebeur et al., 2013). The major sources of MSW generated in Chennai city were found to be households and commercial retail shops (Axelsson and Kvarnström, 2010). Hotels and restaurants in Chennai city are generating 45–60 metric ton of food waste per day. In Chennai city, the wholesale

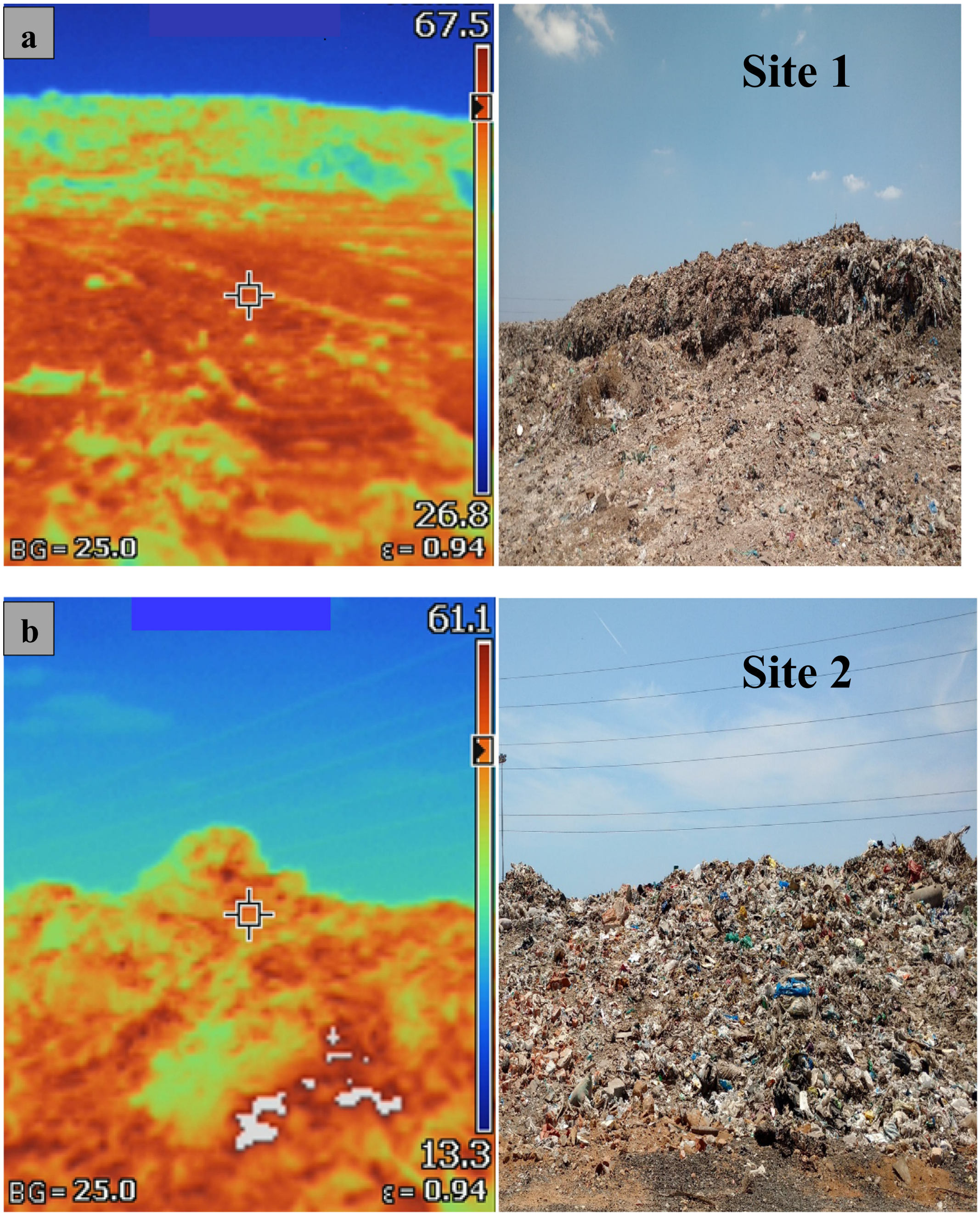

Fig. 2. (a) Temperature profile of waste heap at site 1 captured by thermal imager with real scenario; (b) Temperature profile of waste heap at site 2 captured by thermal imager with real scenario.

market located in Koyambedu generate approximately 100 metric ton of vegetable waste per day, which is being dumped into Perungudi dumpsite (Rakkini and Vincent, 2018).

The plastic wastes were also one of the major constituents of total MSW. The collected plastic waste consists of mainly thin plastic food wraps, drinking water bottles, soft drink bottles, milk packaging cover, grocery bags, and disposable cups. The central pollution control board (CPCB) has reported that around 4000–5000 metric tons of plastic waste generated per day in India, while in Chennai city, 689 metric tons of plastic generated per day (CPCB, 2013). Among plastic waste, it was observed that thin plastic sheets were found to be dominated than plastic bottles and cups. The widespread use of thin plastic sheets at hotels and restaurants for packing and serving the food (CEE, 2018) could be the main reason behind the generation of a huge quantity of plastic sheets. Furthermore, the low price of thin plastic bags resulted in its use for selling goods by roadside vendors and small commercial shops. Besides, plastics under 20-μm thickness have difficulty in recycling resulted in its disposal at open dumpsites.

Paper waste (newspaper, office paper, magazines, and tissue paper) constitutes approximately 7% of total MSW stream. Tissue paper was found to be dominated than newspaper and office paper and mostly generated by the hotels and restaurants. The results indicated that the informal sector mostly recovered newspaper, magazines and office paper at disposal sites. Apart from the organic and plastic waste, construction and demolition waste constitute a significant portion (10%) of the total MSW generated in Chennai city. A recent study reported that Chennai city generates 1.14

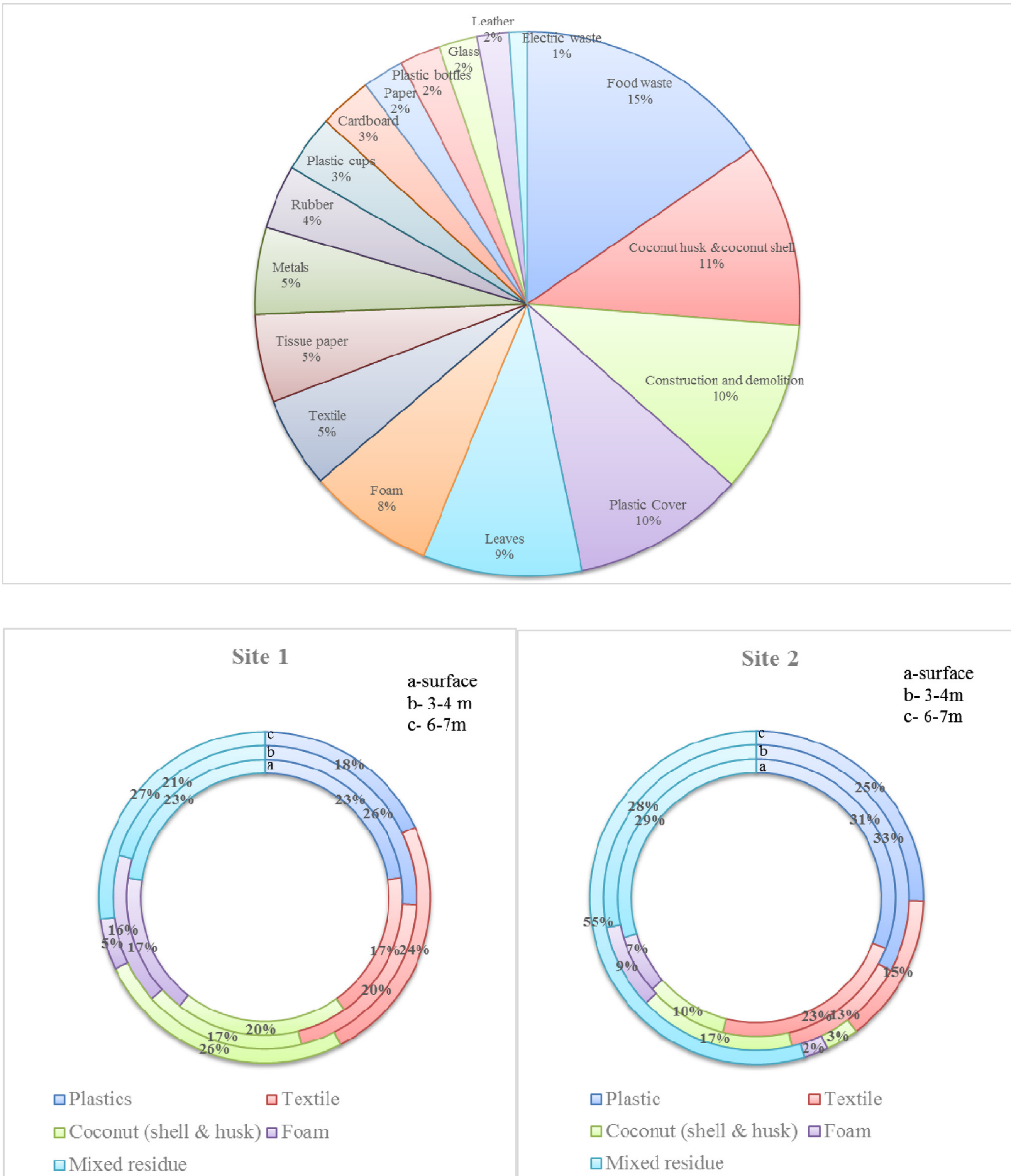

Fig. 3. (a) Composition of fresh MSW samples collected from dumpsite. (b) Composition of excavated MSW samples collected at two sites in dumpsite.

metric tons of construction and demolition waste which amounts to 175 kg capita/year (Ram and Kalidindi, 2017), owing to rapid urbanization. It was found to be that construction and demolition waste samples mainly consists of cement concrete, cement plaster, rubble, and stones. 8% of total MSW was constituted by styrofoam. In recent years, gaining popularity of lightweight polymer foam in packaging industries for various sectors results in the generation of styrofoam waste. The compositional analysis of MSW revealed that more than 35% of putrescible waste has the potential for composting. More than 10% of total MSW alone consists of plastic bottles and cups; plastic cover can be recycled and re-used. The results also revealed that approximately 62% of MSW was combustible materials (plastics, paper, textile, rubber, cardboard, yard waste, and coconut husks) and 30% of MSW consisted of recyclable materials (plastics, paper, cardboard, and metals). Whereas, other metro cities have the compostable fraction of 42–62% and a recyclable fraction of 11–22% (Kumar et al., 2009; Thitame et al., 2010). Micro-level establishments of compost and biogas plants by Greater Chennai City Corporation in recent years might be the reason behind the lower compostable fraction. A higher fraction of recyclable items in MSW is also due to dense population, lifestyle changes, and economic growth rate.

The hand-sorted waste components of excavated old MSW samples collected at two locations in MSW dumpsite are shown in Fig. 3b. MSW samples collected at different depths in two locations at the dumpsite were analyzed. The age of depthwise waste at 3–4 m and 6–7 m was said to be around 5–10 and 15–20 years, respectively. The observed components were plastics, styrofoam, coconut waste, textile, and mixed residue. The mixed residue is an unidentifiable mixture of organic matter and soil with a particle size less than 100 μm. The plastics (23–31%) were found to be a major waste at surfaces of two locations followed by mixed residue (23–29%), textile (17–23%) and coconut shells (10–20%). The mixed residue (28–55%) and plastics (25–33%) were found to be higher at different depths of two sites. At site 1 and site 2, the quantity of combustible MSW components such as plastics, styrofoam, coconut, and textile was higher at 3–4 m depth as compared to surface and 6–7 m depth. These waste components take a long time to disintegrate entirely and were found to be in a partially degraded form at different depths.

Table 1 shows the comparison between the composition of combustible items such as plastics, textile, styrofoam and coconut waste in fresh and old waste collected from the dumpsite. In Table 1, we assumed the paper, tissue paper, cardboard, garden waste and C &D waste in fresh waste gradually turns to the mixed residue in years (Alvarez et al., 2009; Sangamithirai et al., 2015). The absence of other recyclable items such as glass, metals, electric wire and leather in old waste samples as compared to fresh MSW composition which may be recovered by rag pickers during disposal at the dumpsite. Table 1 shows the quantity of combustible items in old MSW varied from fresh MSW. The results indicated that recycling of plastics has an impact on the less amount of plastic waste in fresh MSW as compared to old MSW. Styrofoam constitutes a significant portion of fresh MSW composition in recent years may be attributed to the packaging and food industries and people's purchasing habits. Population and economic growth were inextricably linked to variations in MSW composition in Chennai city over the past years (Fig. A1). It was observed that old wastes have more resource potential for waste to energy (W to E) options than fresh MSW. Landfill mining and recovering of old combustible components which can be utilized for waste to energy (W to E) treatment options.

4.3. Proximate and ultimate analysis of fresh and old MSW

Table 2 provides characteristics of fresh MSW such as MC, VC, CHNS-O, HHV, and LHV.

Table 1
Comparison between fresh and Old MSW composition.

MSW components	Mass percentage of MSW composition			
	Fresh	Old		
		Surface	3–4 m	6–7 m
Plastics	19.04	27.63	25.23	29.18
Foam	8.93	9.43	6.31	3.7
Textile	6.41	7.9	7.13	7.97
Coconut husk and shell	12.87	15.25	19.43	15
Mixed residue	54.43	39.8	41.9	44.22

Moisture content: MC is an important characteristic which can determine the processing and treatment of MSW such as biological or thermal treatment. MC of MSW depends on waste categories, waste type, and local climatic conditions. Among the MSW components like food waste, styrofoam and tissue paper were found to be having higher MC. The biodegradable MSW components have more MC than non-biodegradable components. Chennai city is coming under tropical dry, and wet climatic conditions also have a profound influence on MC of fresh MSW samples that are being dumped into the dumpsite. The MC results presented here in this study were within the range as compared to the range reported in the past research (Tchobanoglous et al., 1993). MC of excavated old MSW samples at site 1 and site 2 was found to be increased with depth (Tables 3 and 4). ANOVA results showed that MC of MSW samples such as plastics, textile, styrofoam, coconut, and the mixed residue was varied at different depths (Table A.2). Moisture is a crucial factor in MSW degradation. Veluchamy et al. (2017) reported the influence of MC on anaerobic degradation of lignocellulosic organic waste components and observed the higher CH_4 production with a threshold limit of MC varied between 80% and 85%.

Volatile solids: VSs of fresh and old MSW components are listed in Tables 2–4. Among the MSW components, tissue paper waste (97%) was found to have higher VS followed by cardboard (84%), plastic cover (83%), and styrofoam (82%). The construction and demolition waste had less VS (22%). The MSW components collected at the study site showed high volatile organic matter. VS of some excavated materials such as textile (surface: 77–79%, 3–4 m: 62–68%, 6–7 m: 53–61%) and styrofoam (surface:70–78%, 3–4 m: 63–78%, 6–7 m: 56–66%) collected at both site 1 and site 2 decreased with increased depth was attributed adherent soil on their surface. VS of coconut (surface: 61–65%, 3–4 m: 62–69%, 6–7 m: 78–80%) and plastics (surface: 65–77%, 3–4 m: 66–80%, 6–7 m 78–88%) collected at both site 1 and site 2 was found to be increased with depth (Tables 3 and 4) due to partial degradation. Old waste components were found to have less VS as compared to fresh MSW. Even though, textile and coconut waste in old MSW have higher VS due to its affinity towards sorption of dissolved organic matter. ANOVA results also showed the variation in VS of plastics, textile, styrofoam, coconut, and mixed residue collected at different depths (Table A.2), which indicated the influence of aging and partial degradation on properties of MSW materials.

4.4. Ultimate analysis of fresh and excavated MSW

CHNS-O analysis: The elemental analysis of MSW components showed that C and O were dominant elements. Non-biodegradable MSW components such as rubber (C-83%; H-7%), styrofoam (C-70%; H-8%), and plastics (C-67%; H-7%) contained a higher percentage of C and H. The biodegradable MSW components contained a higher percentage of O like paper (63%), yard waste (57%), food waste (55%), and coconut (49%). Even, the metal waste also showed less amount of C (4%), H (0.5%), and N (0.2%) can be due to the attachment of organic matter on their surfaces. N was detected in high concentration in food waste (2%), textile (1.3%), and yard waste (0.9%), on the other hand, the paper (0.1%) had very less amount of N. High concentration of S was measured in rubber (2%), PET (plastic bottles) (0.4%) and coconut (0.2%). The chemical compositions of fresh MSW sample with and without S were calculated using data provided in Table 2 and represented in Eqs. (2) and (3).

$$\text{Without sulfur} - C_{126.24}H_{196.02}O_{41.02}N\ (\text{without water});\quad C_{126.24}H_{231.49}O_{41.16}N\ (\text{with water}) \tag{2}$$

$$\text{With sulfur} - C_{194.27}H_{301.64}O_{63.13}N_{1.54}S\ (\text{without water});\quad C_{194.27}H_{356.23}O_{63.34}N_{1.54}S\ (\text{with water}) \tag{3}$$

Table 2
Proximate, ultimate analysis and energy content data of fresh MSW samples collected from dumpsite.

MSW components	Parameters									
	Proximate			Ultimate					Energy content	
	MC (%)	VS (%)	Ash (%)	C%	H%	N %	S%	O%	HHV_d (KJ/Kg)	LHV_w (KJ/Kg)
Food waste	56.33	31.00	69.00	37.15	6.63	1.55	0.12	54.55	9320	1239.26
Yard waste (branches & leaves)	15.79	33.42	66.58	36.67	5.47	0.85	0.20	56.81	16,348	12179.98
Coconut (shell & husk)	5.88	60.28	39.72	45.42	5.32	0.19	0.23	48.85	16,131	13871.33
Plastics (cups & bottles)	10.00	63.68	36.21	62.68	4.35	0.23	0.38	32.36	30,567	26312.01
Food plastic cover	17.65	80.41	19.59	71.08	11.51	0.31	0.14	16.97	32,560	23856.43
Plastic cover	15.00	83.40	16.60	69.01	10.23	0.30	0.13	20.33	36,776	28646.21
Textile	19.05	58.00	42.00	41.85	6.23	1.32	0.19	50.42	20,412	14691.79
Paper (mixed)	10.00	85.00	15.00	32.34	4.47	0.14	0.06	62.99	12477.5	10003.92
Tissue paper	43.24	97.12	2.88	41.96	7.03	0.10	0.30	50.61	14,930	5874.17
Cardboard	37.63	84.80	15.20	38.14	6.14	0.20	0.13	55.39	16,498	8021.87
Rubber	1.39	55.00	45.00	70.61	8.08	0.56	1.87	18.88	25074.28	22916.75
Foam	55.56	82.17	17.83	83.58	7.15	0.49	0.17	8.62	19,914	5926.00
C&D waste	3.03	22.00	78.00	23.90	0.88	0.52	0.16	74.54	6679.4	6210.68
Metals	2.79			3.99	0.55	0.20				
Electric wire	0.20									
Glass	0.34									
Mixed	32.89	78.97	21.03	38.98	6.20	0.40	0.13	54.30	19822.09	11138.52

MC-moisture content; VC-volatile content; HHV_d- high heating value (dry basis); LHVw- low heating value (wet basis).

Table 3
Proximate, ultimate analysis and energy content data of old MSW samples collected at site 1.

Sampling locations	Parameters	Styrofoam	Plastics	Coconut (shell & husk)	Textile	Mixed residue
Surface	MC (%)	16.2	19.0	8.6	12.7	9.5
	VS (%)	70.7	77.9	61.7	77.8	21.9
	C %	83.6	71.0	45.4	41.9	6.1
	H%	7.2	15.4	5.9	4.7	0.6
	N %	0.4	0.3	0.2	1.3	0.4
	S%	0.3	0.1	0.2	0.4	0.1
	O%	8.5	13.1	48.2	51.7	92.8
	HHV (KJ/dry Kg)	18145.7	32745.3	14078.0	19436.0	9588.0
	LHV (KJ/wet Kg)	13238.8	22651.2	11351.5	15734.7	8326.0
3–4 m	MC (%)	30.0	28.5	26.3	23.9	16.1
	VS (%)	64.0	80.8	62.8	62.3	25.5
	C %	85.6	69.0	44.2	57.0	6.9
	H%	7.5	13.4	5.4	6.8	0.9
	N %	0.1	0.2	1.3	0.4	0.5
	S%	0.2	0.1	0.1	0.2	0.2
	O%	6.6	17.2	49.0	35.7	91.6
	HHV (KJ/dry Kg)	16226.0	37703.6	15908.8	17193.3	10706.0
	LHV (KJ/wet Kg)	8989.5	23325.8	9895.5	11138.4	8393.3
6–7 m	MC (%)	42.8	48.5	80	79.8	27.3
	VS (%)	56.5	88.8	80.6	53.7	47.4
	C %	91.3	64.9	37.5	68.3	7.1
	H%	7.8	12.9	5.2	13.4	0.9
	N %	0.1	0.2	2.0	0.2	0.6
	S%	0.02	0.04	0.1	0.1	0.2
	O%	0.8	22.0	55.2	18.0	91.2
	HHV (KJ/dry Kg)	13680.0	38786.0	17365.7	15042.7	11145.3
	LHV (KJ/wet Kg)	5075.6	15984.6	3647.1	1913.4	7232.8

C and H content of excavated old MSW components such as textile, and styrofoam were observed to be increased with depth whereas O, N, and S decreased with depth (Tables 3 and 4). C and H content of coconut and plastics were decreased with increased depth. Tchobanoglous et al., (1993) reported that plastics, textiles and styrofoam components which were not readily decomposable organic constituents of MSW. A higher percentage of C and H in plastics, textiles, and styrofoam can be attributed to surface adherence of fine earthen material (compost) resulted from anaerobic decomposition of other organic waste components. A study conducted by Jokela and Rintala (2003), affirmed that anaerobic decomposition could solubilize around 50% N present in organic fractions of MSW. The anaerobic solubilization of N has resulted in its fewer amounts in plastics and textiles. The reason behind the high concentration of N in coconut waste was due to its high affinity towards adsorption of elemental ions. ANOVA results showed the significant difference of CHNS-O in excavated MSW components at different depths (Table A.3).

Energy content: The calorific value/high heating value (HHV) of MSW samples were expressed in the present study based on the dry mass basis. Plastic materials (32560 KJ/Kg) and rubber waste (25074.28 KJ/Kg) have highest HHV whereas, food waste (9320 KJ/Kg) with low HHV. The maximum waste to energy recovery through MSW incineration depends on the lower calorific value of the waste. If the LHV of MSW is higher than 7000 KJ/Kg, then it can be considered for thermal incineration processes (Baawain et al., 2017). Plastics, textile, paper, yard waste, and rubber have higher LHV which can be thermally incinerated without much fuel

Table 4
Proximate, ultimate analysis and energy content data of old MSW samples collected at site 2.

Sampling locations	Parameters	Styrofoam	Plastic	Coconut (shell & husk)	Textile	Mixed residue
Surface	MC (%)	28.0	20.0	11.0	21.0	8.0
	VS (%)	78.0	65.0	65.0	79.3	23.0
	C%	76.5	72.2	45.2	40.8	6.0
	H%	6.8	14.5	6.0	4.0	0.7
	N %	0.2	0.3	0.4	1.1	0.5
	S%	0.2	0.2	0.2	0.2	0.1
	O%	16.2	12.8	48.2	53.9	92.7
	HHV (KJ/dry Kg)	20818.3	37228.7	14752.7	20457.3	9771.2
	LHV (KJ/wet Kg)	12808.3	26117.4	11544.9	14764.6	8638.9
3–4 m	MC (%)	37.5	35.0	52.8	54.6	33.3
	VS (%)	78.5	66.1	69.8	69.0	24.7
	C%	80.0	69.1	44.3	54.6	6.9
	H%	7.0	12.6	6.0	6.1	0.8
	N %	0.2	0.2	1.2	0.7	0.5
	S%	0.2	0.1	0.2	0.1	0.2
	O%	12.5	17.9	48.3	38.4	91.7
	HHV (KJ/dry Kg)	18158.0	38786.0	16761.7	18007.3	10132.7
	LHV (KJ/wet Kg)	8900.4	21585.0	5314.7	5504.8	5774.8
6–7 m	MC (%)	49.0	59.6	78.5	78.6	42.3
	VS (%)	66.5	78.9	78.1	61.6	28.0
	C%	85.9	61.8	40.0	68.3	7.1
	H%	7.5	4.8	5.1	12.4	0.9
	N %	0.2	0.2	1.6	0.2	0.6
	S%	0.2	0.1	0.2	0.03	0.2
	O%	6.2	33.1	53.1	19.1	91.3
	HHV (KJ/dry Kg)	15156.2	41195.0	18007.7	15406.3	11866.0
	LHV (KJ/wet Kg)	4886.6	14117.6	1443.1	1522.6	5617.6

consumption. All MSW components except for food waste and tissue paper were having LHV higher 7000 KJ/Kg (Table 2). A positive correlation between HHV and C (0.72), H (0.55) and a negative correlation of HHV with O (−0.98) was observed. Komilis et al. (2012) indicated that C, H, and O were statically predictors for energy content. Also, they addressed that O content doesn't contribute to the energy content since O can't be combusted by itself. The regression model studies on the energy content of MSW indicated the positive correlation between C, H, and energy content (Komilis et al., 2012; Liu et al., 2012).

HHV of excavated old waste fractions such as plastics and coconut materials have increased as the increase in depths. Excavated MSW components collected from site 1 at 3–4 m depth were found to be having LHV value of higher than 7000 KJ/Kg sufficient enough to imitate self-ignition (Table 3). At site 2, the MSW samples collected at 3–4 m depth showed that only styrofoam and plastics had higher LHV value (Table 4). The mixed residue was found to be having higher LHV so it can be recovered from the dumpsite and can be used as a substitute fuel for waste to energy treatment options. ANOVA results showed the significant difference of HHV and LHV in excavated MSW components at different depths due to the influence of aging (Table A.4).

4.5. Heavy metals of fresh and old MSW

In recent years, heavy metal pollution at open dumpsites is alarmingly increased. Therefore it is important to identify key sources and its contribution to heavy metal pollution. All kinds of MSW components dumped in a commingled stream, heavy metals in them converged together made the dumpsite as a consortium of toxic heavy metals. The heavy metal concentrations of each MSW components collected from dumpsite are shown in Fig. 4a, b, and c. The heavy metals (Zn, Pb, Cu, Cd, Ni, and Cr) present in paper waste (newsprint, magazines and office papers) were likely resulted from the additives to papermaking. Cu content in newsprint and magazines can be attributed to copper phthalocyanine pigment used for cyan coloration (Tucker et al., 2000). Zn as zinc sulfate (ZnS) and zinc oxide (ZnO) was used to increase the opacity of papers whereas ZnO used in the production of photocopy papers. Pb and Ni can result from pigments used for the development of multiple colorants (Mertoglu-Elmas, 2017). ZnO is generally used as vulcanization accelerator which helps sulfur vulcanize the rubber in the tire tread (Adachi and Tainosho, 2004). Most of Zn in tire tread present as ZnO (0.04–1.55%) (Councell et al., 2004). It was found to be rubber waste components were highly enriched with Zn. The plastic and textile waste components were highly enriched with Cd, Cr, Cu, Fe, Ni, Pb, V, and Zn (Fig. 4a and b). Bode et al. (1990) reported that red, orange and yellow colored plastic materials contain high Cd due to its usage as pigments. Cd was also used as chemical compounds for stabilizers in plastic materials (European Commission, 2002). Cr, Cu, Cd, and Pb were widely used as chemical compounds for textile dye (Halimoon and Yin, 2010). Electrical waste such as wire and discarded batteries in the study site was mainly constituted of Cu, Fe, Cr, Zn, Pb, and Mg (Fig. 4c). The heavy metal analysis revealed that higher concentration of THMs in various MSW components cause severe environmental risks either by its leaching to groundwater and soil or by open burning. Most of MSW components disposed at the dumpsite were recyclable items. Therefore, good practice of recycling can reduce not only the burden of dumpsite but also to protect the environment and public health.

The previous studies in the same study area indicated that heavy metal content in leachate collected from the dumpsite was within the permissible levels (Banuraman and Madavan, 2011). The less content of heavy metals in leachate can be attributed to anaerobic waste stabilization of MSW components. The pH of leachate in the study area was found to be around 7 which slow the metal mobility. The study area is an open dumpsite where rainwater enters, subsequently increased the leachate production. The generated leachate percolates through the pores of MSW components towards the lower level of the dumpsite. The distribution of heavy metals in the similar kind of MSW components collected from different depths seemed to be different. The heavy metals

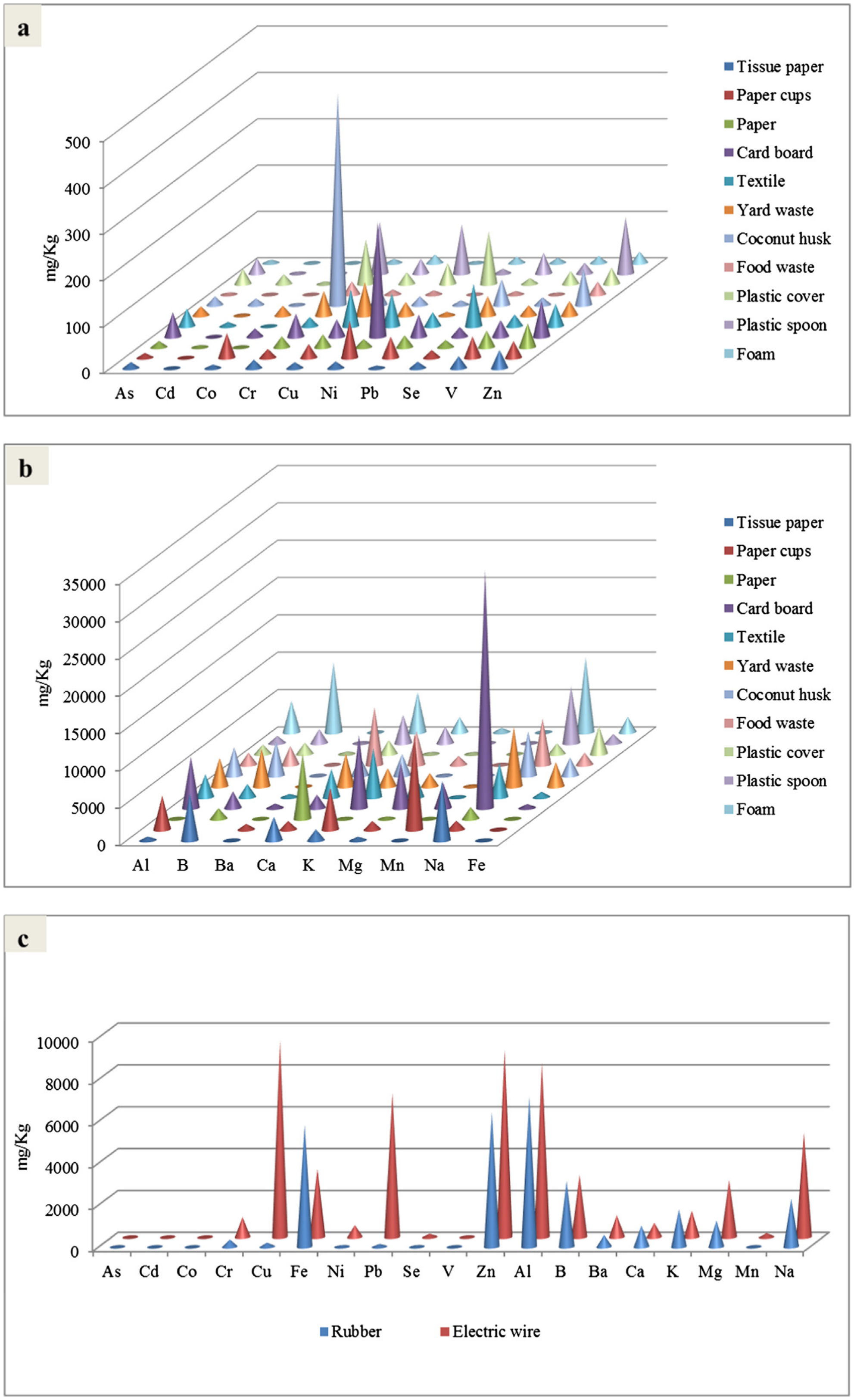

Fig. 4. (a and b) Heavy metal concentrations of fresh MSW samples collected at MSW dumpsite; (c) Heavy metal concentrations of rubber and electric wire waste.

content in plastic components were decreased with increased depth whereas heavy metal content in textile, coconut, and styrofoam waste components increased with increased depth (Fig. 5a and b). The adsorption properties of textile, coconut and styrofoam waste components make them reservoirs for the deposition of leahed heavy metals. At different depths, these waste components may be transformed from a reservoir to a source which is capable of adsorbing toxic heavy metals.

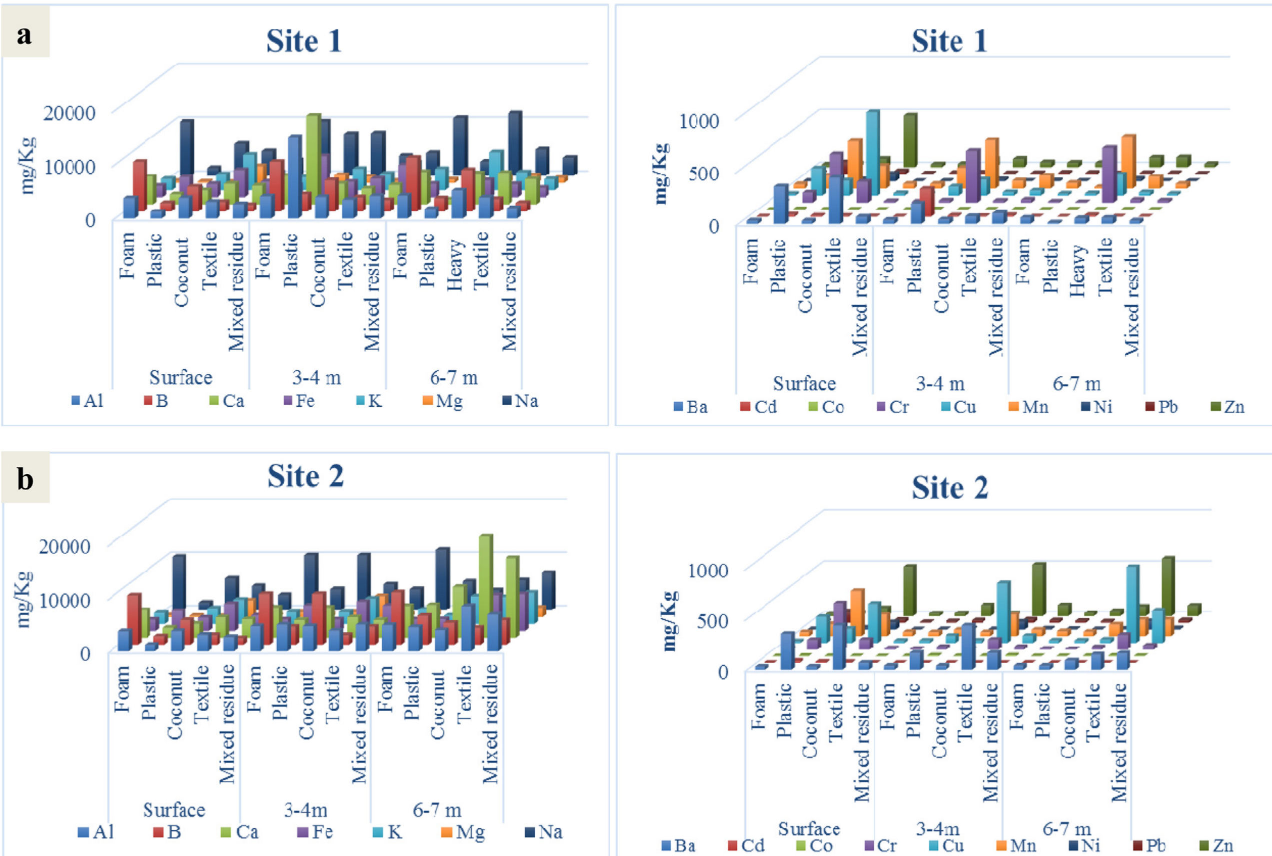

Fig. 5. (a) Heavy metal concentration of MSW samples collected from different depths at site 1; (b) Heavy metal concentration of MSW samples collected from different depths at site 2.

4.6. Gaseous emissions from an open MSW dumpsite

The monitoring of CH_4, CO and H_2S can be used as an indication in the possibility of a hotspot formation. Inflammable biogases produced during the anaerobic degradation of the biodegradable MSW. Gaseous emissions from MSW landfills last for longer periods. CH_4 is lighter than air, when, generated methane tends to escape through pores and filled with air pockets in the waste pile. Hotspots are formed when the temperature increases due to anaerobic decomposition, they can migrate throughout the dumpsite, thus creating smoldering events. Deep-seated fires in dumpsite happened when CH_4 gas comes in contact with hotspots in a confined environment of the waste piles (Copping et al., 2007). Results of gaseous emission measurements at dumpsite indicated that CH_4 concentration was observed to be higher at depths in the waste pile. CH_4 gas was measured to be 5.12 ± 0.16% and 5.85 ± 0.12% in 3–4 m and 6–7 m depths, respectively. The lower explosive limit and the upper explosive limit for CH_4 in the air at ambient temperature and atmospheric pressure is 5 to 15%, respectively (Gas, 2013). The observed concentrations of CH_4 higher than the LEL (5%) may increase the likelihood of fire incidents. From the results of CH_4 concentration, we estimated CH_4 emission flux for the Perungudi dumpsite was found to be 200 ± 8.7 mg m^{-2} hr^{-1}. The previous study conducted in Perungudi dumpsite by Jha et al. (2008) showed that CH_4 emission flux results were varied from 0.9 to 9.94 mg m^{-2} hr^{-1}in 2003 and 1.8 to 433 mg m^{-2} hr^{-1}in 2004. These variations in CH_4 emission fluxes may be attributed to either change in the quantity of organic matter in MSW composition or due to change in stages of anaerobic degradation.

CO is a good indicator of the presence of partial burning processes. The observed CO concentration was higher at 3–4 m (313.7 ± 5.8 ppm) than at 6–7 m (3.82 ± 1.3 ppm). Henderson and Sperling (2001) reported that a higher concentration of CO might be attributed to pyrolytic processes within the waste pile. It can also represent the potential source of smoldering events if CO concentration is more than 100 ppm. Hydrogen in the form of H_2S was formed in the early stages of anaerobic degradation of MSW. H_2S concentration was observed to be 148.59 ± 5.7, 31.1 ± 2.7, and 10.15 ± 2.2 ppm at the surface, 3–4 m, and 6–7 m depths, respectively. H_2S concentration was observed to be higher in the surface of the old waste pile where young waste in its decomposition would emit H_2S at the surface (148.59 ± 5.7 ppm), whereas older waste below 6–7 m undergoing anaerobic decomposition would produce more CH_4 (5.85 ± 0.12%) (Copping et al., 2007).

4.7. The factors influencing the spontaneous combustion of MSW at the dumpsite

The compositional analysis of fresh MSW results showed that approximately 50% by weight of total MSW consisted of organic fraction (Fig. 3a). The dumpsite consisted of mixed waste and are complex systems that stimulate interlinked biological and chemical exothermic reactions. The microbial decomposition of organic waste may be initiated at the temperature of 25–45 °C and moisture content of 20–24% (Buggeln and Rynk, 2002). The temperature was measured at different depths of waste heaps at two sites observed to be higher at 3–4 m (53–63 °C). The heat generated by biotic and abiotic processes could increase the temperature of waste heaps. At different depths, slow pyrolysis may be initiated when the temperature rises above 35 °C (Moqbel and Reinhart, 2012). Heat generated within the waste piles cannot dissipate uniformly, due to the insulating properties of the MSW. The accumulation of heat produced within a waste pile depends on the balance between the rate of internal heat generation and rate of heat loss to the external ambient environment. When the internal heat generation rate is higher than the heat loss, a "critical" internal temperature may be reached that leads to hotspot development within the waste. The subsurface fires to initiate when the generated heat is not dissipated uniformly at which thermal runaway ignition happens. Self-heating by biological and chemical oxidations of commingled organic MSW components include textile, coconut, the mixed residue can trigger the SC at ordinary ambient temperatures with access to atmospheric oxygen (Buggeln and Rynk, 2002). The mixed residue is enriched with fine organic matter (particle size <100 μm) and its progressive self-heating over a period of time may be a crucial prelude to spontaneous ignition.

Moqbel et al. (2010) reported that some heavy metal compounds (Na, K, Fe, Cr, Pb) exhibit smoldering inducing effects. A positive correlation was found between heavy metals such as Ba (0.68), Cu (0.64), Pb (0.65), Fe (0.5), Cd (0.51) and HHV. The chemical oxidation by leachate may also promote smoldering ignition of MSW (Moqbel et al., 2010). The increased concentration of heavy metals in excavated components such as textile, coconut, and styrofoam can contribute to smoldering of MSW at different depths under the preferable conditions. The presence of moisture in the form of water may increase the liquid–phase oxidation and acid hydrolysis of MSW, subsequently make contributions to the heat release rate. Approximately 25% of moisture content was reported to be an optimum for SC. Drier conditions are expected to lessen the microbial activity, while wetter conditions will reduce the mass porosity and restrict potential increases in temperature. The observed MC of different waste components collected at different depths favors the anaerobic decomposition of MSW into CH_4, CO_2, H_2S and other gases, which can migrate through porous waste materials and filled the air pockets in the waste pile. The progressive self-heating of waste materials and the air pockets filled with inflammable gases are hotspots where smoldering fires are likely to happen.

The waste compaction is a common practice at MSW disposal sites to reduce the bulkiness and conserve the airspace thus to extend the lifespan of dumpsites and landfills. Kubler (1982) reported that pile compaction resulted in the filling of spaces between larger particles with fines. The pile compaction processes lead to heat retention within the piles might reduce oxygen penetration but also cause higher heat generation via fast pyrolysis. The pile compaction also reduces the convective heat transfer and increase pile temperature causing the SC to initiate. Heat retention and loss within a pile can be achieved through maximum air convection from a pile by featuring the "chimney effect." A narrow and tall waste pile will provide a better opportunity for heat loss than short pile with a broad and flattop based pile (Kubler, 1982). On the other hand, shallow and broad dumpsites are more sensitive to solar heating which further increase the temperature of waste.

The chemical and physical characterization of excavated MSW samples collected from two different depths of site 1 and site 2 revealed that waste at 3–4 m depth of dumpsite is prone to spontaneous fires. Preventing the spontaneous fires at the dumpsite is primarily depends on regular monitoring regime, site management and waste acceptance procedures that avoid the dumping of commingled MSW. The installment of probes for checking the landfill gas concentrations and temperature which can further help in controlling the fires. Capping the waste piles with clay-like materials for sealing of air-ingress sources and disposal of waste in smaller waste piles instead of larger piles also prevent the fires.

4.8. Municipal solid waste management in Chennai City- a way forward

Updating the current database on origin, quality, quantity, and waste management services will help in redesigning and evaluating the waste management strategies. In our study, the dumpsite MSW was comprehensively analyzed to determine the potential of dumpsite MSW to be considered as a resource rather than as waste. We have identified lack of source separation, uncontrollable disposal in open isolated areas, lack of education and public awareness on effective management of waste, lack of financial resources to build amenities for waste management as some of the many problems in the MSW management in Chennai city. We are pressing on the significance of waste minimization, maximization of value from waste and delivery of knowledge for current predicament in MSW management. With a holistic collaboration between the public sector, private sector, and industry, waste can be handled more resourcefully and even reduced. The present scenario in MSW disposal at dumpsite and suggested measures are shown in Fig. A.2.

Source-based segregation aids resource recovery and also helps in avoiding spontaneous fires due to mixed dumping. Meager success in source-based segregation has been achieved through the use of color-coded bins commissioned by authorities at households, institutes, office buildings, commercial shops, hotels, and restaurants. Involvement of information technology (IT) sector in app/web development along with global positioning system (GPS) applications provided the real-time information on waste collection time and truck route, special collection on request, recycle center and community bins. Sensor-based smart bins can also be encouraged for efficient collection by sending the location-wise real-time status of bins to waste collectors. The apps also can be as the information center and E-learning system about managing the waste that can change people's perceptions and attitude regarding the waste. The innovative web/app applications can be an ideal platform for interaction among citizens, informal sector and ULBs. The implementation of economic incentives for the public to recover recyclable materials will drive the voluntary participation of the society in MSW management.

Additionally, the waste generation can be significantly reduced by bringing policies such as "pay as you throw system" (Qing et al., 2010). The informal sectors (waste pickers, and scrap dealers or kabadi system) handle resource recovery and collection of recyclable waste components (Linzner and Lange, 2013). In spite of the role played by the informal sector in bringing down waste quantities through resource recovery, not much recognition has been given. Integrating the informal sector to the formal sector along with legal and professional recognition will reduce the overall MSW management costs, create job opportunities and provide support to recycling industries. Packaging wastes including disposable cups, cutlery, carton boxes, and corrugated cardboard constitute a significant portion of MSW in recent years. Promoting the use of biodegradable packaging materials instead of non-biodegradable materials at restaurants, cafeterias, and commercial shops which can be effectively composted as means of a potential resource.

Landfill mining combined with W to E treatment technologies can convert the challenging old waste piles to wealth oriented revenue. MSW landfill mining also frequently referred to as landfill reclamation is the process of excavating previously dumped waste materials in reducing the landfill volume and recovering the recyclable and combustible components (Jain et al., 2013). Landfill mining has been practiced in some parts of Europe and U.S (Jain et al., 2013) can be adopted for the present scenario. Site-specific operational and technical considerations can be taken into account before undertaking the full-scale project based on lessons learned from the previous landfill mining projects (Jain et al., 2013). The recovered soil can be used as an intermediate soil cover. The current study results showed the excavated old combustible materials have higher energy content that can be opted for waste to energy treatment technologies (Rizwan et al., 2018). Further, reclaimed land can be converted into sanitary landfills through step by step approach (Jain et al., 2013).

Knowledge transfer in the form of information campaigns, workshops for the public and private sector, exchange of best practice among stakeholders can bring new dimensions to waste management. The consortium of skilled experts includes engineers, business professionals, academicians and logistic experts at every level of waste management hierarchy can put forward solutions and innovative technologies for better management.

5. Conclusion

In the present study, an in-depth analysis of old and fresh MSW from the 30-year old open dumpsite was carried out to identify the suitable options for the management of MSW. The compositional analysis results showed that more than 35% of putrescible waste has the potential for composting. Effective recovery of recyclable items (30% of fresh MSW) can curb up to 720 tons of waste from reaching the dumpsite. Heavy metal analysis of old waste at different depths showed that textile, coconut, and styrofoam waste components were reservoirs for leached heavy metals. ANOVA results showed that a significant difference existed in MC, VS, CHNS-O, HHV, and LHV of plastics, textile, styrofoam, coconut and mixed residue collected at different depths. Measurements of gaseous emissions at dumpsite showed that concentration of CH_4 ($5.85 \pm 0.12\%$) and CO (313.7 ± 5.8 ppm) was observed to be higher below 3 m depth, whereas H_2S concentration (148.59 ± 5.7 ppm) was found to be higher at the surface of waste heaps. The chemical and physical characterization of depth-wise MSW samples from site 1 and site 2 revealed that spontaneous fires were prone to happen at 3–4 m depth in the dumpsite.

Disposal at exhausted dumpsites can cause water, land and air pollution in addition to the loss of a valuable resource that could have been recovered from the waste. The study results showed that old MSW samples have a large quantity of combustible materials which can be preferably converted to energy. In the light of present scenario, promoting awareness regarding resource value of waste, co-operation among actors involved in the waste management chain, and knowledge transfer may improve the overall efficiency of MSW management.

Acknowledgments

We thank the commissioner and superintending engineer of solid waste management department, Greater Chennai Corporation for their cooperation and support during the present study. We are thankful to staff members of Perungudi MSW dumpsite for their logistics support. We are grateful towards Head, Sophisticated Analytical Instruments Facility (SAIF), IIT Madras, Chennai, India, for their help during the analysis.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2018.12.022.

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