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ORIGINAL ARTICLE

Effect of depth of landfill on the characteristics of soil-like material of aged waste: a case study of Bhalswa dumpsite, India

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Abstract

This study characterizes the municipal solid waste (MSW) accumulated for more than 25 years at Bhalswa dumpsite, Delhi, India. 50 undisturbed samples of MSW were collected in Shelby tubes (75 mm dia.) at a regular depth interval of 3 m up to a depth of 35 m from the top and mid-height of the 65 m-high dumpsite. Total unit weight, organic content, water content, and particle size distribution of the total MSW were analyzed for different depths to understand the matrix of the waste mass accumulated inside the dump. Soil-like material (SLM, < 4.75 mm) screened from the total MSW was also analyzed for organic content, heavy metals (total and leachable), soluble salts, and release of dark-colored leachate. Total unit weight of MSW slightly increased, whereas organic content slightly decreased in the lower sections of the boreholes. An increase in the percentage of SLM was observed with an increase in the depth of the waste. The total heavy metal concentration of chromium, lead and zinc increased by depth. The leachable heavy metal concentration of chromium and nickel increased with depth. The findings of this study can be useful for mining dumpsites and suggesting various options for its re-use in developing countries like India.

Keywords Contaminants of concern · Dumpsites · Effect of depth · Municipal solid waste · Soil-like material

Introduction

Landfilling is the most widely adopted method of solid waste disposal worldwide. India generates around 62 million tons of MSW per year, out of which more than 50% is dumped into open dumping sites without any segregation [1–3]. Several large municipal solid waste dumps in major cities continuously cause subsurface contamination and pollution in the nearby vicinity. These dumps have risen to heights of 50–70 m covering valuable land due to the huge accumulation of waste from the past 30–50 years (also called legacy waste) and now continuously pose threats to human life [4, 5]. To reduce the quantity of accumulated legacy waste at dumps and reclaiming the site for other beneficial purposes, landfill mining can be considered to be a viable option [6–8]. Landfill mining is generally defined as the extraction of resources from landfills. Preliminary trials of landfill mining have been started at almost all the major dumpsites of India in the last year [9]. However, the potential of landfill mining depends on the resource and energy recovery from the lying resources in a landfill. Hence, for developing any landfill mining (LFM) project, it is imperative to conduct a preliminary characterization study to have an in-depth analysis of the dumpsite [10–12].

Physicochemical characteristics are necessary for evaluating the feasibility of a landfill mining project. For example, determining the capacity of recovery and recycling facility, bulk density is an important parameter. Similarly, the moisture content of excavated waste is crucial to determine the valorization route (thermal, recycling, or biological treatment) of the waste fraction and depends on several parameters such as location, climatic conditions, leachate generation, and waste type. Some heavy metals can cause highly toxic and/or bio-accumulative effects and are persistent in the environment, as well as circulate throughout the food chain [13, 14]. The leaching of soluble salts from SLM may

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increase the salinity of the surrounding subsoil and cause contamination of the nearby groundwater. The leaching of dark-colored leachate can cause coloration of the surrounding water bodies and groundwater. The presence of color affects consumer's acceptance of drinking water [15, 16].

As landfill mining has gained major attention in the recent past in India, the characterization of waste accumulated inside the dumpsite is a primary step to assess the feasibility of reuse of excavated materials. Most of the previous studies have focused on the collection of samples from trial pits from the top few metres only [17, 18]. This study appears to be the first study in India involving a detailed investigation on the undisturbed samples of old MSW from a regular depth interval up to 35 m from the top and mid-height of a dumpsite.

The purpose of this study is to provide foundational knowledge of the composition and characteristics of excavated material from a specific MSW dumpsite, which is important for planning the landfill reclamation/mining activities. To identify the influence of depth of waste on the characteristics of total MSW and soil-like material (SLM), the undisturbed samples of MSW were collected from a regular depth interval of every 2.25 m up to a depth of 35 m from the top and mid-height of Bhalswa dumpsite at Delhi, India. Comprehensive field and laboratory studies were carried out to evaluate the physical characteristics and contamination potential of accumulated waste. The physical characteristics of total MSW samples (collected inside the undisturbed sampling tubes) including total unit weight, organic content, moisture content, and particle size distribution were determined. The contaminants of concerns including heavy metals (total as well as leachable), soluble salts and release of dark-colored leachate were determined in the SLM (collected after screening MSW through 4.75 mm sieve).

Materials and methods

Study site

The open dumping of municipal solid waste at Bhalswa dumpsite was started in the year 1990 and the site is still active. The dumpsite spreads over an area of approximately 56 acres and is located next to Bhalswa Horseshoe Lake and is about 10 km west of the River Yamuna in New Delhi, India. On an average ,3000 tons of MSW is dumped daily at the dumpsite and the height of the dumpsite varies between 60 and 65 m. The total quantity of waste accumulated at the dumpsite is about 8 million tons.

Site investigation at Bhalswa dumpsite

The site investigation was conducted to design a cover system and gas and leachate extraction wells at the site. The investigation was carried out by M/s BEIL Research and Consultancy Pvt. Ltd. (BRCPL), Vadodara, India. A total of 28 boreholes (16 in the vicinity of toe level, 6 in the vicinity of mid-height, and 6 in the vicinity of top level) were drilled to carry out a detailed investigation of the deposited waste. The location of boreholes is shown in Figure S1. Undisturbed samples (UDS) were collected by drilling 150 mm dia. boreholes up to 35 m depth from the top level and mid-height and retrieving UDS using Shelby tubes at every 3 m depth interval. The scope of the present study was mainly limited to the drilling of six boreholes (4 located at the top level and 2 at the mid-height) for a detailed laboratory investigation.

Location of boreholes

The MSW samples of six boreholes were specifically collected for the present study and have been analyzed. WBH5, WBH 7, WBH 10, and WBH 12 are the boreholes drilled from the top level of the dumpsite. WBH 1 and WBH 4 are the boreholes drilled from the mid-height of the dumpsite.

Sampling methodology and nature of samples collected

The details of the boreholes analyzed in the present study is shown in Table 1. The pictorial representation of sampling is shown in Fig. 1a-f.

The boreholes were drilled using percussion drilling to the specified depth in accordance with IS:1892 [19]. The diameter of the borehole was 150 mm. To prevent caving of the boreholes, a casing was used to keep the boreholes stable.

'Undisturbed' samples were collected by attaching 75 mm diameter thin-walled 'Shelby' tubes and driving the sampling tube using a 63.5 kg hammer in accordance with IS:2132 [20]. The tubes were sealed with wax at both ends and transported to the laboratory for further examination and testing. It is emphasized that the sampling tubes did not collect oversized fraction greater than 75 mm as well as cloths/textiles etc.

The samples of total MSW were collected from a regular interval of every 3 m from each borehole, starting from 2.25 m from the top level. In total, 55 samples of undisturbed MSW were collected for laboratory investigations on total MSW. To assess the effect of depth on the characteristics of SLM, the MSW samples of 3 to 4 UDS tubes

Table 1 Location of boreholes analyzed in the present study

S no.	Location	Samples ID	Existing ground level (m)	Borehole termination depth (m)	Borehole termination level (m)
1	Top level	WBH 5	RL 265.14	25.45	RL 239.69
2		WBH 7	RL 270.57	25.45	RL 245.12
3		WBH 10	RL 270.21	25.45	RL 244.76
4		WBH 12	RL 269.19	25.45	RL 243.74
5	Mid-height	WBH 1	RL 235.99	32.25	RL 204.49
6		WBH 4	RL 228.89	35.25	RL 193.64

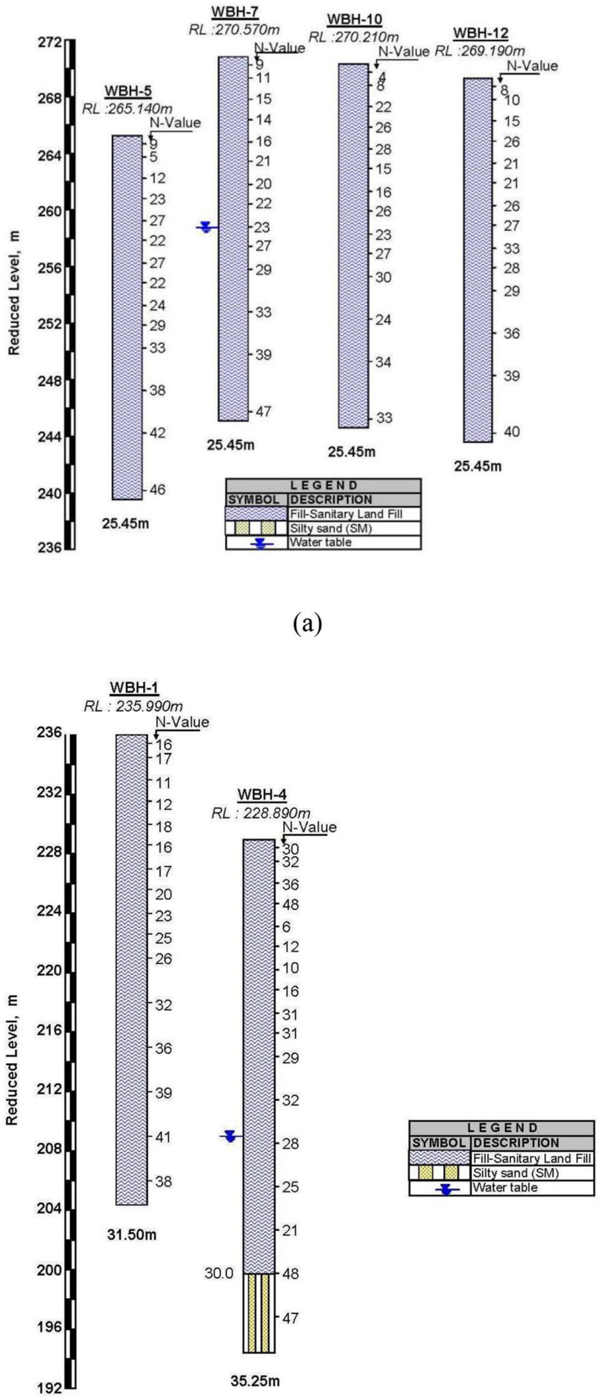
Fig. 1 Sampling through drilling, **a** Drilling from the top level of dumpsite, **b** drilling from the mid-height of dumpsite, **c** bailer operation at 20 m depth from the top of the dumpsite, **d** sample in sampling tube retrieved from boreholes, **e** sample extrusion in the laboratory

(corresponding to depths of 2.25–11.25 m, 11.25–20.25 m, and 20.25–35.25 m) collected from six boreholes were mixed and screened after air-drying (5–7 days) through a 4.75 mm sieve.

Standard penetration test

Standard penetration tests (SPT) were conducted in the boreholes at 3.0 m depth interval. The tests were conducted by connecting a split spoon sampler to rods and driving it by 45 cm using a 63.5 kg automatic trip hammer falling freely from a height of 75 cm. The SPT values of six boreholes investigated in the present study are shown in Fig. 2. The SPT values of other boreholes are shown in Figures S2 and S3.

The tests were conducted in accordance with IS 2131 [21]. The SPT 'N'- values are described as follows:



(a)

(b)

Fig. 2 SPT values of borehole drilled from the **a** top level; **b** mid-height

(i) The number of blows for each 15 cm of penetration of the split spoon sampler was recorded.

(ii) The blows required to penetrate the initial 15 cm of the split spoon for sampling the sampler were ignored due to the possible presence of loose materials or cuttings from drilling operation.

(iii) The cumulative number of blows required to penetrate the balance 30 cm of the 45 cm split spoon sampler is termed the SPT value or '*N*' value.

Characterization of total MSW and SLM

Total MSW

Total MSW in the present study has been defined as the unsegregated municipal solid waste collected from a regular depth interval at Bhalswa dumpsite. The following parameters were determined in the undisturbed samples of total MSW.

Total unit weight The UDS samples after collecting from the boreholes were immediately brought to the laboratory and the total unit weight was calculated by measuring the total weight of the MSW samples and volume of the sampling tube by using the following formula:

$\gamma = W/V$.

$\gamma =$ total unit weight (g/cm^3).

W = weight of MSW sample (g).

V = Volume of the sampling tube (cm^3).

Water content and organic content In the present study, the moisture content was determined by drying waste at 60 °C to a constant mass and the organic content was determined by heating the dried waste (at 60 °C) to 550 (±50 °C) in a muffle furnace in accordance with Monkare et al. [22] and Zekkos et al. [23].

Soil-like material (SLM)

To assess the effect of depth on the characteristics of soil-like material (SLM, <4.75 mm), MSW samples of 3–4 UDS tubes were mixed together and screened through 4.75 mm sieve after partial air-drying for 5–7 days. The following parameters were investigated in the samples of SLM.

Contaminants of concern To determine the total heavy metals, SLM was first ground to a size below 0.075 mm in a ball mill. 0.2 – 0.5 g of sample was then digested in a microwave digester (Multiwave GO 7000, Anton Paar) using aqua regia (mixture of HNO_3 and HCl in a molar ratio of 1:3) following USEPA [24]. The digested mixture after cooling down to room temperature was filtered through Whatman No. 42 filter paper into a volumetric flask (50 mL) and filled up to the required volume using ultrapure water. All the metals including Cr, Ni, Cu, Zn, As, Cd, and Pb were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS).

Leachable heavy metals were determined through a single batch leaching test according to the Swedish standard method [25]. This was also adopted on SLM by the previous investigators Kaartinen et al. [26] and Wanka et al. [27]. A liquid to solid ratio of 10 L/kg was maintained in a rotary shaker for 24 h using deionized water. In brief, 10 g of SLM was mixed with 100 mL DI water, followed by shaking for 24 h at 100 rpm using a mechanical rotary shaker. After shaking, it was allowed to settle for some time, the solution was then filtered through 2.5 µm filter paper (Whatman no. 42) and further centrifuged at 8000 rpm for 10 min. The leachable heavy metals in the filtered samples were analyzed using ICP-MS.

Total soluble solids were determined as per the procedure outlined in IS 2720 [28] (1:10 dilution). Sulfates and chlorides were determined by turbidimetric method and argentometric titration method, respectively, in accordance with APHA [29].

The intensity of the color of dark-colored leachate (1:10 dilution) from SLM was measured in the platinum–cobalt unit (PCU) using a Lovibond Tintometer.

Linear regression model

A linear regression was carried out to analyze the relationship between physicochemical parameters and depth. A regression model enables to capture trends, i.e., increasing or decreasing concentrations by depth. The regressions were calculated for each parameter separately using all samples collectively (simple linear regression). A *p* value smaller than 0.05 indicates a statistically significant trend.

Results and discussion

The effect of depth of waste on the characteristics of total municipal solid waste (MSW) and soil-like material (SLM) is presented in this section.

Characteristics of total MSW

The effect of depth on the following characteristics of waste were examined:

(a) Total unit weight.
(b) Organic content.
(c) Water content.

Variation of total unit weight with depth of waste

The total unit weight of undisturbed samples of total MSW collected at regular depth intervals from all the six boreholes ranged between 1.25 and 1.90 g/cm^3 (excluding outliers) with an average of 1.58 g/cm^3. The values obtained in the present study are significantly higher than the values reported by previous investigators in the literature, 1.3–1.6 g/cm^3 [30] and 0.37–1.2 g/cm^3 [31].

From Fig. 3a, b, it can be seen that there is a wide variation in the total unit weight of MSW samples which reflects the heterogeneity of the material. The total unit weight varies between 1.25 and 1.75 g/cm^3 in the boreholes excavated from the top level (RL 270 to 238; Fig. 3a); however, it

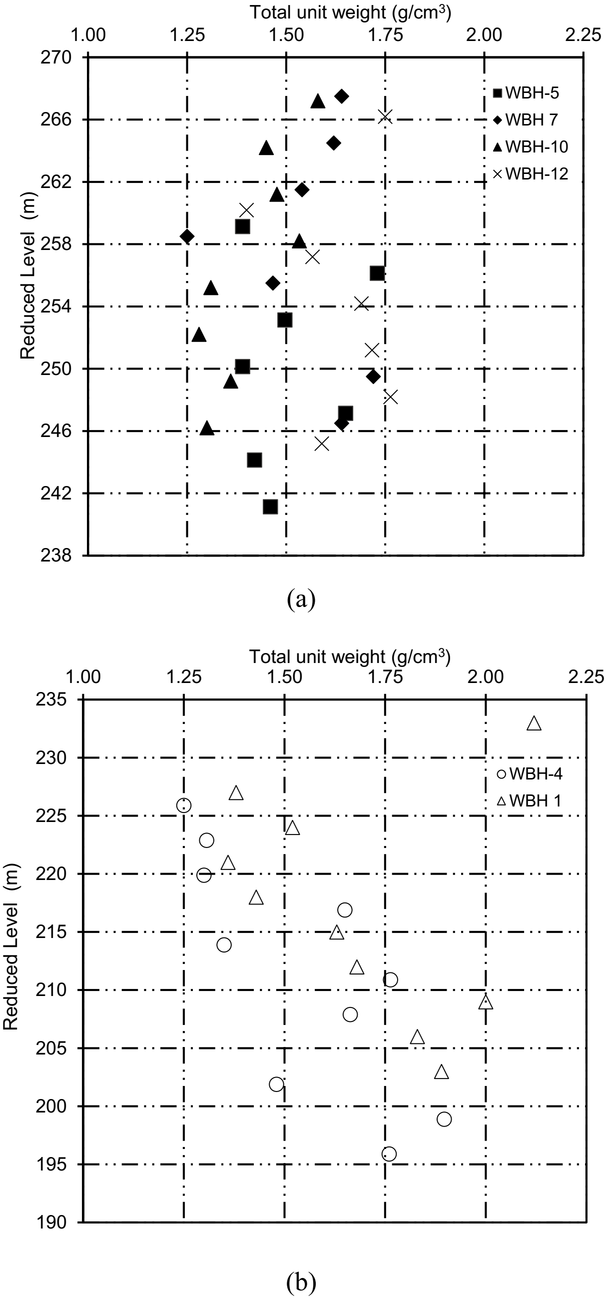


Fig. 3 Variation of total unit weight of total MSW with depth of waste: **a** top level; **b** mid-height

increases slightly from 1.75 to 1.90 g/cm^3 in the boreholes excavated from the mid-height of the dumpsite (RL 235 to 190 m; Fig. 3b). These findings are consistent with similar trends reported in literature [30, 31]. Linear regression analysis showed a highly significant regression between the total unit weight and depth (*p* value 0.002).

Variation of organic content with depth of waste

The biodegradable fraction (an indirect representation of organic content) in the fresh MSW in the Indian dumpsites is reported to be in the range of 40–60% by various investigations in the literature [32–34]. The organic content obtained in the present study varies between 10.2 and 25.4% in the undisturbed samples of total MSW collected from all the six boreholes. The significant reduction in the organic content from 40–60% to 10.2–25.4% can be attributed to the presence of high amount of biodegradable content in Indian MSW, most of which gets degraded in 2–3 years after the disposal.

Figure 4 shows the variation of organic content with an increase in the depth of waste. The regression analysis resulted in a *p* value of 0.068 which is just above the required *p* value (0.05) of a significant regression. A wide variation is observed in organic content, which reflects the heterogeneity of the material. A slight decrease in the organic content of the total MSW sample can be seen in the lower sections of boreholes which is in accordance with the similar observations reported in the literature [35–38]. A relatively higher organic content (22.5–26.9%) was observed in the lower section of WBH 10 in comparison to the other boreholes and no special reason could be attributed to it.

Variation of water content with depth of waste

The water content determined by oven drying (at 60 °C) of total MSW samples collected at regular depth intervals from all the six boreholes ranged between 23 and 42%.

Figure 5 shows the variation of water content with an increase in the depth of waste. However, a regression analysis could not verify a significant trend (*p* value 0.84). A wide range of variation of water content was observed. The water content slightly increases in 10–15 m depth of the waste and then slightly decreases toward the lower end of the boreholes. A clear trend of water content reduction with an increase in the depth of landfill is reported in the literature [37, 38]. Relatively higher water content was observed in the lower sections of WBH 10, which is in accordance with the higher values of organic content (in the lower sections of WBH 10) as shown in "Variation of organic content with depth of waste".

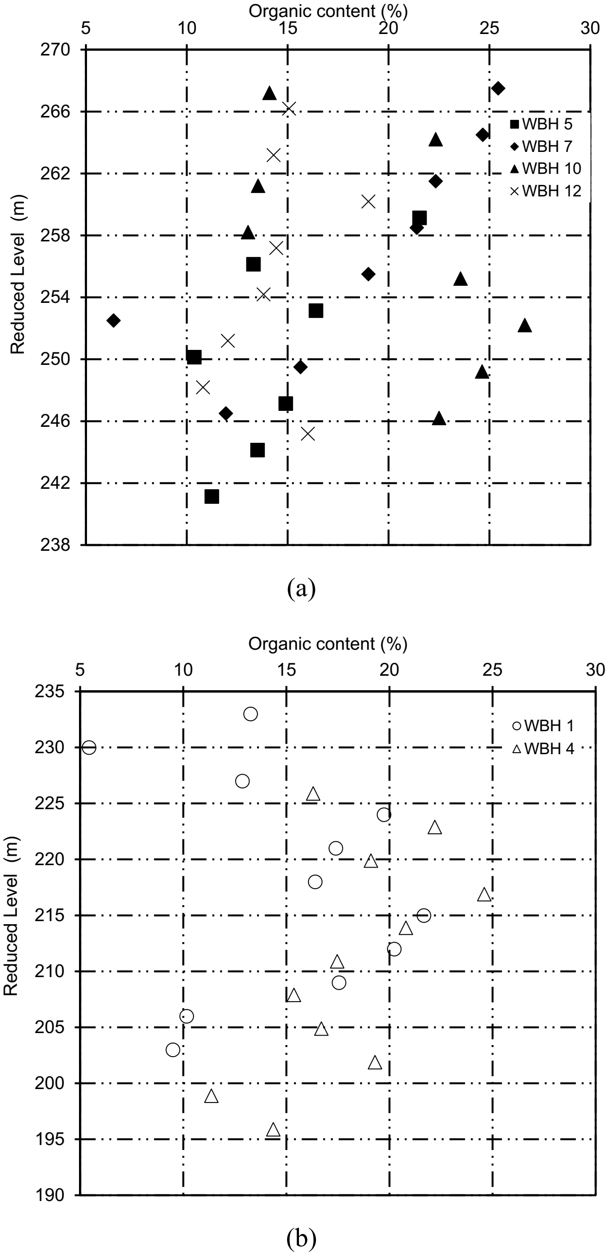
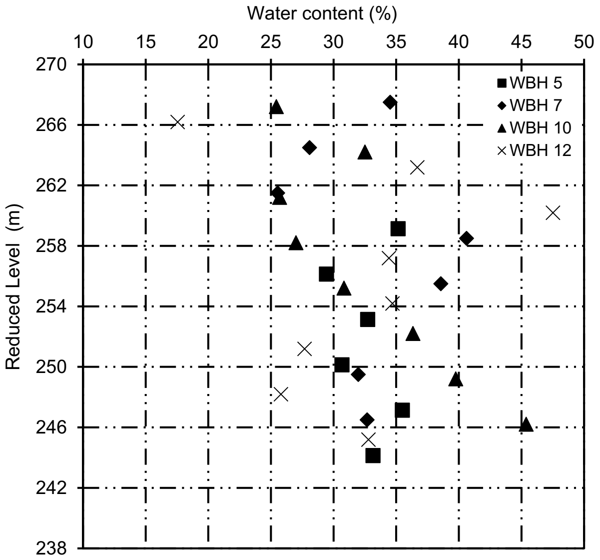


Fig. 4 Variation of organic content of total MSW with depth of waste: **a** top level; **b** mid-height

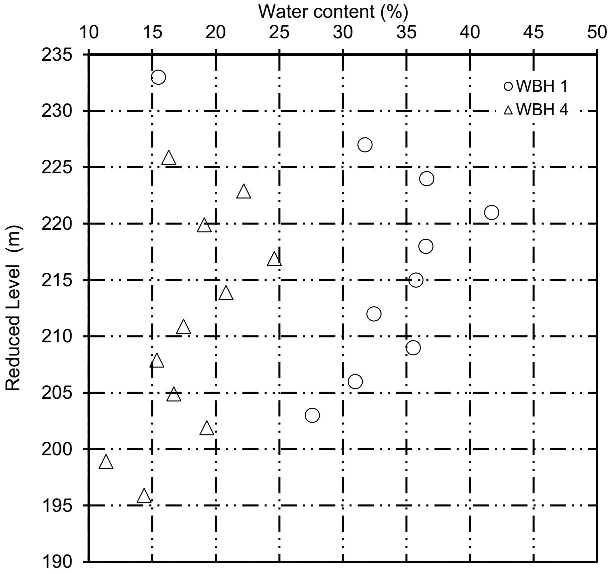
Characteristics of soil-like material (SLM)

The effect of depth of waste on the following properties of SLM were assessed:

- Percentage of SLM.
- Organic content.
- Contaminants of concern.



(a)



(b)

Fig. 5 Variation of water content of total MSW with depth of waste: **a** top level; **b** mid-height

Variation of percentage of SLM with depth of waste

The MSW samples of 3–4 UDS tubes collected were mixed together and screened through 20 mm and 4.75 mm sieve to determine the various fractions (based on size) of total MSW. The screening was performed on air-dried and pulverized samples of MSW without washing. The percentage of various fractions is shown in Table S1. It can be noted that coarse gravel-sized fraction (20–80 mm), fine gravel-sized fraction (4.75–20 mm), and soil-sized fraction (0–4.75 mm) vary between 8 and 25%, 24 and –45%, and 30 and 65%, respectively, in the samples of all six boreholes.

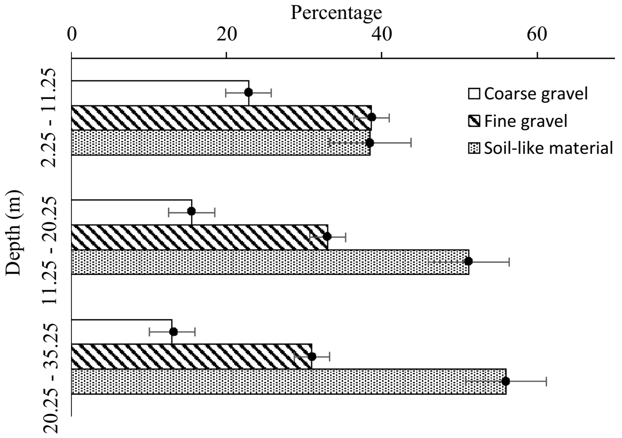


Fig. 6 Variation of average percentage of fractions of total MSW with depth

The variation of various fractions (based on the average results of various fraction of all the six boreholes, listed in last three rows of Table S1) with depth is shown in Fig. 6. It can be noted that the percentage of SLM increases (by an order of 15%) with an increase in the depth of waste, whereas the gravel-sized material decreases with an increase in the depth of waste. The higher content of SLM in MSW samples at larger depths of the boreholes can perhaps be attributed to the downward movement of fines with infiltrating rain water/leachate and higher degradation of waste located at a greater depth.

Variation of organic content in SLM with depth of waste

As mentioned in “Variation of organic content with depth of waste”, the organic content of total MSW was found between 10.2% and 25.4%. The organic content in SLM collected from all six boreholes was found to vary between 7.0 and 21.5%, whereas in the background soils of the nearby area the organic content was found to be 0.8–1.2%.

The variation of organic content with depth (based on the average results of boreholes corresponding to the depth interval of every 10 m, listed in last row of Table S2) is shown in Fig. 7. Relatively higher concentration of organic content was observed in the 2.25–11.25 m section of the boreholes which can be attributed to the presence of a relatively high amount of fast biodegradable waste in the top section of the dumpsite which has undergone less biodegradation. It can also be noted that a marginal decrease (by an order of 3%) in organic content was observed with an increase in the depth of waste as shown in Fig. 7. Calculations of the regression analysis did not result in a significant trend (p value = 0.46).

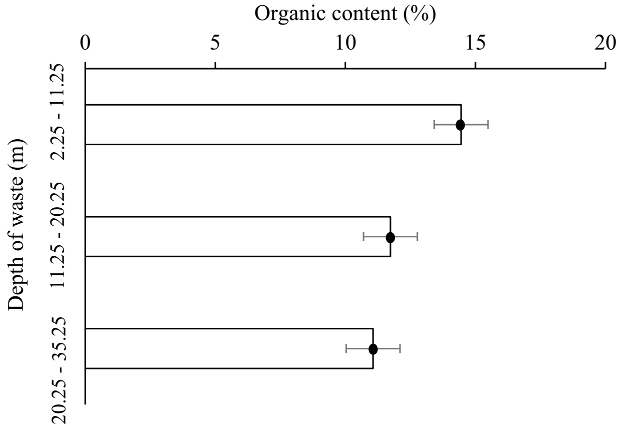


Fig. 7 Variation of average percentage of organic content in SLM with depth of waste

Variation of contaminants of concern in SLM with depth of waste

The effect of depth of waste on the following contaminants of concern were assessed:

- Total heavy metals.
- Leachable heavy metals.
- Total soluble solids.
- Release of dark-colored leachate.

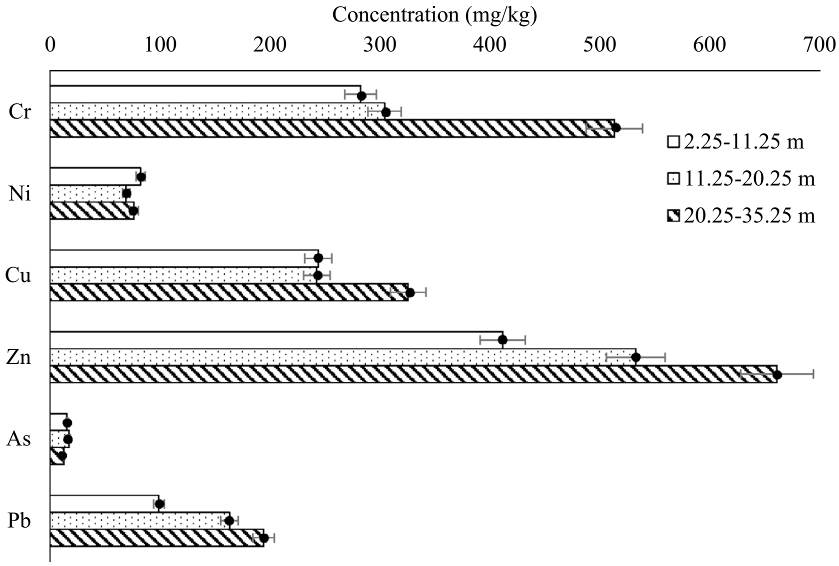
Total heavy metals The total heavy metal concentration of Cr, Ni, Cu, Zn, As, Cd, and Pb was found to be 110–650 mg/kg, 20–170 mg/kg, 66–500 mg/kg, 240–920 mg/kg, 3–60 mg/kg, and 0.5–4.5 mg/kg, 40–230 mg/kg, respectively. All the metals were found to be significantly higher in the SLM than in the background soil (listed in the last row of Table S3).

The variation of total heavy metals with the depth of waste (based on the average results of all the six boreholes corresponding to the depth interval of every 10 m, listed in Table S3) is shown in Fig. 8. It can be seen that Cr, Cu, and Zn showed a significant increase (by an order of 50–80%) with an increase in the depth of waste. Pb showed a slight increase with an increase in the depth of waste. However, Ni and As did not show any significant change with an increase in the depth of waste. On the basis of the regression analysis, a trend between concentration and depth could only be identified for Cu; however, the *p* value (0.07) was just above the significance level of 0.05. In addition, the *p* values of Cr (0.13), Zn (0.18) and Pb (0.24) indicated a possible trend than those of Cd (0.46), As (0.65) and Ni (0.77). A similar trend was observed on an Indian dumpsite by Singh and Chandel [11] and Esakku et al. [39]; however, no significant correlation was observed in the concentration of heavy metals with the depth of landfill by Adelopo et al. [40].

Leachable heavy metals The leachable metal concentration of Cr, Ni, Cu, Zn, As, Cd, and Pb was found to be 0.88–3.09 mg/kg, 0.64–1.98 mg/kg, 0.75–2.48 mg/kg, 1.47–2.29 mg/kg, 0.08–0.42 mg/kg, 0.042–0.092 mg/kg, and 0.17–0.63 mg/kg, respectively. The leachable heavy metals in the SLM were found to be significantly higher than those in the background soils.

The variation of average leachable heavy metals across the depth (based on the average results of all the six boreholes corresponding to the depth interval of every 10 m, listed in Table S4) is shown in Fig. 9. Leachable heavy metals showed a similar trend to that of the total heavy

Fig. 8 Variation of average concentration of total heavy metals in SLM with depth of waste



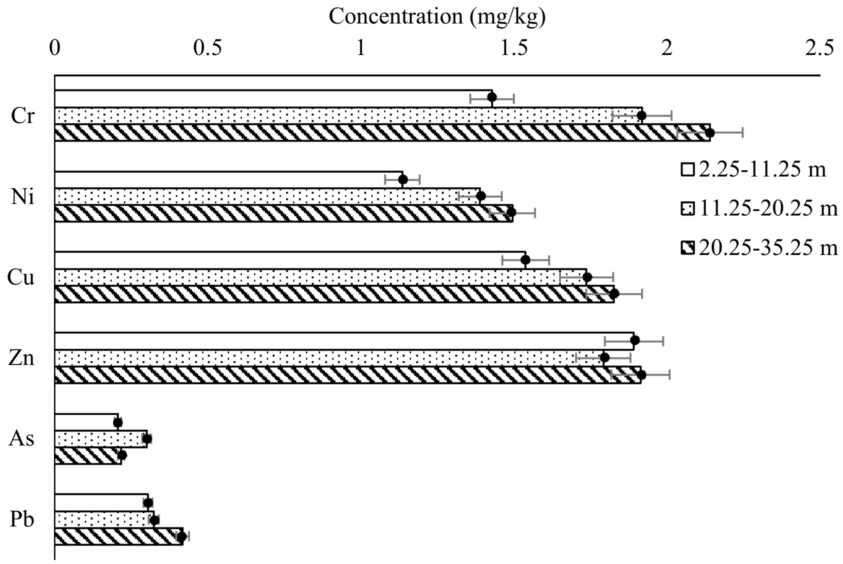


Fig. 9 Variation of average concentration of leachable heavy metals in SLM with depth of waste

metals (as shown in Fig. 8). It can be seen that Cr, Ni, and Cu showed a significant increase (20–50%) with an increase in the depth of waste. A slight increase in Pb was observed with an increase in the depth of waste. However, Zn and As did not show considerable effect with an increase in the depth of waste. The calculations of a regression analysis for leachable heavy metals showed less trends between concentrations and depth than for total heavy metal concentrations. The calculations of regression analysis for leachable heavy metals showed less trend between concentrations and depth than for total heavy metal concentrations. The *p* value of chromium (0.12) proved to be the closest to the significance level of 0.05, whereas the *p* value of Ni was 0.30, Cu 0.32, Cd 0.61, Zn 0.72 and As 0.91.

Total soluble solids (including sulfates and chlorides) Total soluble solids, sulfates, and chlorides ranged 9800–29,000 mg/kg, 4580–12,000 mg/kg, and 3350–10,500 mg/kg, respectively, in SLM samples of all the six boreholes, whereas in the background soils they were found to be 500–700 mg/kg, 300–350 mg/kg, and 200–250 mg/kg, respectively.

The variation of soluble salts with depth (based on the average results of all the six boreholes corresponding to the depth interval of every 10 m, listed in Table S5) is shown in Fig. 10. An increase in the soluble salts (by an order of 10–15%) with an increase in the depth of waste can be seen from Fig. 10. The higher concentration of salts at the greater depth can be attributed to the downward movement of salts with infiltrating precipitation. The regression analysis indicated for soluble salts a greater trend between concentration and depth than for the leachable heavy metals. However, the *p* values of total soluble solids (0.24), sulfate (0.26) and chlorine (0.37) remained above the significance level of 0.05.

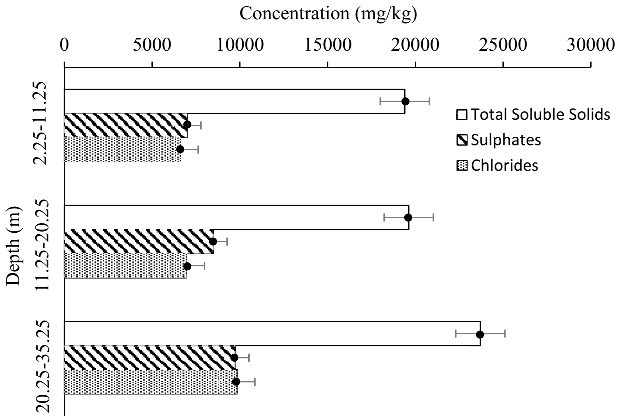


Fig. 10 Variation of average concentration of soluble salts in SLM with depth of waste

Release of dark-colored leachate The intensity of dark-colored leachate in the SLM samples collected from all the six boreholes was found to vary between 225 and 615 PCU. The intensity of color obtained for the samples of boreholes was found to be significantly higher than that in the background soils collected from the nearby area of the dumpsite (25–30 PCU).

The variation of the intensity of color with depth (based on the average results of all the six boreholes corresponding to the depth interval of every 10 m, listed in Table S6) is shown in Fig. 11. It can be seen that the average intensity of color decreases from 450 to 350 PCU as the depth of waste increases from 11.25 to 35.25 m. This can be attributed to the less organic content in the lower section of the

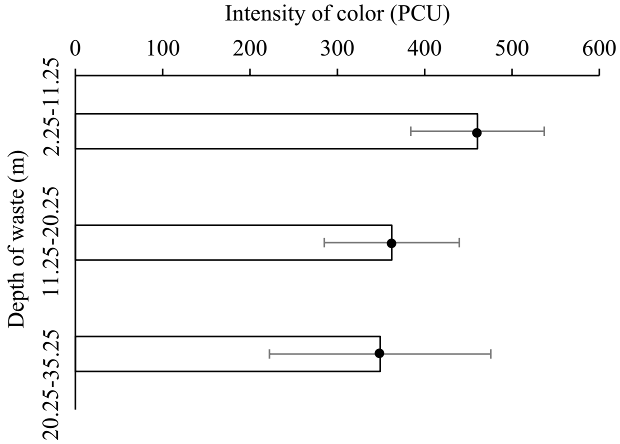


Fig. 11 Average intensity of color in SLM with depth of waste

dumpsite as shown in Fig. 7. The results of a regression analysis resulted in a p value of 0.23.

Conclusions

As landfill mining has gained a major attention in the recent past in India, characterization of waste accumulated inside the dumpsite is a primary step to assess the feasibility of reuse of excavated materials. Most of the studies conducted in the past have been focused on the collection of samples from trial pits from the top few meters only. This is perhaps the first study in India to carry out a detailed investigation on the undisturbed samples of old MSW from a regular depth interval up to 35 m from the top and mid-height of the dumpsite. The characterization of total MSW samples and soil-like material (SLM) recovered at regular depth intervals of every 3 m at Bhalswa dumpsite (up to 35 m) was carried out to investigate the effect of depth of waste on the characteristics of waste. The total unit weight, organic content, and water content of the undisturbed samples of total MSW from the boreholes have shown a wide variation across the depth of the dumpsite, which reflects the heterogeneity of waste mass accumulated inside the dumpsite. A significant reduction in the organic content with an increase in the depth of waste is reported in the literature; however, no sharp reduction in the organic content was observed in the present study. Rapid decomposition of organic materials under climatic conditions of India and granular structure of organic matter hindering transportation might result in this even distribution. In contrast, the weight of waste increased significantly by depth. In addition, an increase in the percentage of soil-like material (<4.75 mm) was observed with increase in the depth of waste which can be attributed to the downward movement of fines with infiltrating precipitation.

The scope of the present study was limited to the characterization of excavated MSW based on organic content, total unit weight, water content, as well as heavy metals characteristics of soil-like material. Other contaminations such as organic pollutants could be studied in future research. Geotechnical characteristics (compressibility, compaction, hydraulic conductivity, and shear strength) are also important for an extensive investigation before reusing landfilled mined waste in offsite applications.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-022-01447-0.

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